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ENVIRONMENTALISM AND ENVIRONMENTAL CHANGE AS IT AFFECTS CANADIAN DEFENCE POLICY AND OPERATIONS:

PART THREE; ARCTIC ISSUES

BY DR. C. M. TUCKER

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ARCTIC STRATEGIC STUDIES

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ABSTRACT

The purpose of this report is to provide an analytical synthesis of various scientific issues relating to climate change in arctic Canada and to discuss their implications for future planning and operations of the Department of National Defence. This paper is one of a continuing series of analyses on the general issue of global warming.

RÉSUMÉ

Ce rapport de projet est une analyse de l'impact des changements climatiques sur l'environnement du grand nord canadien, ainsi que de l'effet de ces changements sur la planification et les opérations du ministère de la Défense nationale (MDN). De plus, il importe de noter que cette étude et fait partie d'une plus grande recherche sur le concept du réchauffement de la planète.

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EXECUTIVE SUMMARY

1. Some 40% of Canada's landmass is located north of the 60th parallel. This region is surrounded by 2/3 of our coastline and offshore waters, and shares the Arctic Ocean, the world's fourth largest, with seven other countries. It is because of these facts, among others, that the strategic and operational issues related to global climate change as it relates to arctic Canada are of concern to the Department of National Defence (DND). In a policy context, we need to know the security and sovereignty implications of issues such as; the possible melting of sea ice between the Arctic Islands, and the northward shift of forest and tundra. From an operations point-of-view, the practical problems of melting permafrost (perennially frozen ground) that underlies about half of Canada's land surface and significantly changed meteorological conditions, will require modifications to existing infrastructure and revised planning for, amongst others, future construction, materiel and exercises.

2. The political and economic infrastructure of Canada, as in most societies, has developed with an underlying assumption of a variable climatic environment which is stable about a long-term mean. The greenhouse warming of the atmosphere whatever its magnitude, undermines this assumption, and thus, as well as environmental change, substantial social and economic disruption will also take place. It is anticipated that over the next half century, virtually that period of time since the end of the Second World War, human activities will have substantially altered global climate by enhancing the earth's natural green house effect.

3. The initial purpose of this paper is to describe in some detail the natural phenomena and ecosystems in arctic Canada that are susceptible to modification from the effects of global warming as they are perceived by current researchers in the various fields. Much of the work herein consists of a review of pertinent scientific literature on various aspects of the topics chosen. The logic of this approach in a policy-related paper is that

readers should be able to have ready access to at least a précis of the basic scientific arguments that are driving the issues being considered. The second purpose of the study is to relate the diverse changes that might occur in the North within the next fifty years to possible future policy and operations for DND.

Meteorology

4. It is reasonable to expect that future meteorological conditions in arctic Canada may be more difficult to deal with from an operations point-of view, despite a considerable amelioration, from those existing today. Though there is some disagreement about the range and time frame, a general consensus among climate modellers is that the annual global average temperature will rise from the 1950-80 value of 15.3° C to 16.8-19.8° C by the year 2035, i.e., approximately 0.3° C per decade. In the Arctic, the warming is anticipated to be less than the global average during the summer, perhaps as little as half a degree. However, during the winter a dramatic increase in temperature is expected, as much as 8° C according to the Canadian Climate Model. This would be twice the global average.

5. Though not entirely conclusive, predictions also hold that there will be increases in precipitation throughout the year; 10-50% in summer and by up to 60% in winter. Part of this increase will be from rainfall which now falls in southern Canada and is expected to shift northward. Increased rainfall would tend to enhance evaporation rates and cloud cover, reducing insolation and ground surface temperatures, resulting in a negative feedback to a rise in mean annual surface temperature.

6. In essence, we can expect a much warmer, wetter Arctic with far more unsettled meteorological conditions 50 years from now. Coastal areas will be significantly foggier because of increased open water conditions and increased overall moisture. For similar reasons, one can expect increased low stratus cloud cover in summer.

7. As a result of these changes, the requirements for DND aviation meteorological services are likely to increase in the coming decades. Present DND missions in the North include interception of aircraft and airborne vehicles, surveillance/sovereignty, search and rescue, and tactical and logistical air support for land force exercises. With climatic amelioration, many of these roles could conceivably increase in the future. Similarly, if DND activity increases in arctic waters, because of less severe meteorological conditions and increased commercial shipping in the North, marine forecast speed and accuracy will also need to be bolstered to be better able to predict events such as coastal fogs, ice conditions and sea states, etc.

8. New technologies will, therefore, be required to aid forecasting. The areal coverage of weather observations 'north of 60' already falls well short of the World Meteorological Office recommended 150 km grid density. To remedy this, automatic weather stations, radar coverage and enhanced satellite surveillance and communications use would need to be considered. There will increasingly be a need for an expanded military meteorological presence in the Arctic. Careful regard should be given to its equipment, location and its association with Atmospheric Environment Services as this organization's services are enhanced in the North. Research on the effects of changed meteorological conditions as they might influence the North Warning System should also be considered.

Sea Ice

9. Both numerical models and paleoclimatic research concur that sea ice extent and dynamics have not been static over time, nor are they likely to remain so with climatic amelioration over the next century. For the moment this does not give cause for concern. Nevertheless, when considering the future, there are significant geopolitical, and military operational/strategic issues that will need to be considered as a result.

10. From a geopolitical aspect, Canada will have to consider how it intends to defend its 1973 claim to sovereignty over 'internal' arctic waters. Under present conditions, whether the Northwest Passage is or is not a 'Canadian internal waterway' may be considered by many people to be a moot point since

it is not, by most standards, navigable. For the majority of the year, transit is blocked by ice by in its widest part, Viscount Melville Sound, and it is necessary for vessels to retreat to passage through the Prince of Wales Strait between Banks and Victoria Islands, as happened with the voyages of the supertanker S.S. Manhattan in 1969 and the icebreaker U.S.S. Polar Sea in 1985. On both these occasions there was considerable protest from the Canadian public. Notably, these events were about 15 years apart which tends to be the frequency of discussion on Canadian control of activities in these waters. With increased economic activity likely to be brought about by an enhanced ice-free shipping season and freer access to natural resources, the level of debate (and DND's participation in it) will certainly increase.

11. The original Manhattan voyage resulted in the enactment of The Canadian Arctic Waters Pollution Act in 1970. The legislation provided for the protection of ocean waters north of 60°N latitude and for a distance of 160 km offshore. Although at the time the Act was opposed by the United States, it has been seen in Canada as good for the environment and for strengthening our sovereignty over arctic internal waters. Obviously, any increase in shipping due to climatic amelioration will put added pressure on DND resources to assist in protecting Canadian interests in this area.

12. Another aspect of this is that one needs naval vessels capable of operating in ice-infested waters - something that Canada currently does not possess. At the present time, without heavy icebreaker support, which itself is limited, Canada's navy can only operate in two oceans. Even from a commercial viewpoint, only CANARCTIC's ice breaking freighter, M.V. Arctic, is capable of operating virtually year round in ice-covered waters. Consideration will probably be given to our naval operational future in the Arctic and our ability to design and build vessels tailored for that environment.

13. To better assess DND's future in arctic waters, further scientific research is needed on sea ice extent and dynamics, especially how it relates to global warming. There are also strategic aspects to the results of this

research. It is important to know how sound propagation will change in arctic water, how thermoclines will shift, circulation patterns will be modified, and ice will ground. One of the predictions of a changing ice regime is that as ice cover lessens in the Arctic Basin, icebergs, ice floes and 'bergy bits' will become more frequent along the east coast. Aspects of these subjects are important for anti-submarine warfare and arctic acoustic surveillance.

Permafrost

14. In general, the effects of projected climate warming during the next several decades will deepen the active layer and initiate a northward retreat of permafrost. It is expected that a 2° C global warming would shift the southern boundary of the climatic zone currently associated with permafrost north and northeast by at least 500-700 km. The southern extent of permafrost will lag behind this, moving only some 25-50 km in the next 40-50 years. The depth of the active layer is expected to increase by one metre during the same time frame. The melting of permafrost would also result in the release of methane and , to a lesser extent, CO_2 from previously frozen biological material and from gas hydrates. The extent to which this will enhance the greenhouse effect is uncertain, but it could be about 1° C by the middle of the next century.

15. From DND's point-of-view, these events will have a significant operational impact. In practical terms, increased terrain instability would lead to major concerns for the viability of roads, airfields, dams, reservoirs, and other engineered foundations located within affected areas. Deepening of the active layer would subject foundations to continuing deformations as a result of thaw settlement. Decreases in the amount of ground ice present would lead to reductions in the mechanical strength of the associated soil as well as increases in permeability, both of which will have significant consequences for engineering of facilities and overland mobility.

16. It is possible given the current state of knowledge and design constraints to predict areas that will be particularly susceptible to

permafrost degradation. Most of the Forward Operating Locations (FOL) airstrips are located within this zone, though it must be noted that the affected areas are highly dependent on which climate model is chosen as a reference. A recent cooperative study between Energy Mines and National Defence has mapped subsurface conditions at FOL sites in Inuvik and Rankin Inlet with ground penetrating radar. Zones of massive ground ice were detected below the proposed extensions. It was concluded that in areas slated for construction or modification of drainage patterns, the identification of subsurface permafrost features ahead of events can play an important part in the planning process to avoid future problems. In fact, current engineering at the Rankin Inlet FOL expansion is allowing for some degree of future climate change.

17. There are several approaches to designing structures located within permafrost. These include: a) disregard the thermal regime of underlying permafrost and apply conventional techniques of construction from temperate regions; b) thaw permafrost prior to construction; c) allow for thawing during construction, and; d) maintain permafrost in a frozen state. Of these options, a) is a very risky procedure, b) is very expensive and not widely used, and c) is only of benefit for short term construction or where materials are thaw-stable. Option d) is currently in wide use throughout the North. Raised utilidors in Inuvik, and insulated runways at Rankin Inlet are examples of such a design philosophy.

18. Another issue related to permafrost integrity that DND may need to analyze is that of overland summer mobility. Although we assume that given our current level of activity in the North there is no mobility problem (since most transport is by air) this situation may not remain so in the future. In addition, since the existing road network will be especially vulnerable to thaw, perhaps catastrophically, the design parameters of low ground pressure / high mobility vehicles for the Canadian Forces (CF) might profitably be given renewed consideration. Further pro-active research is also needed on the question of permafrost stability as it pertains to our existing infrastructure. These types of projects may be done through the Defence

Research Establishments in conjunction with groups like the National Research Council and such private corporations as Nodwell or General Motors Canada, all of whom are involved in mobility or cold weather research.

Tree line and Ecozones

19. In general, the practical aspects of northern shifting tree lines and ecosystems would only concern DND in so far as they relate to the economic activities of Canadians in the North. It is concluded that migration of tree lines and ecozones will happen with less rapidity than will the disintegration of permafrost, for example. Nevertheless, as southerners find more reasons to populate the North, DND will become involved in appropriate activities in the territory.

20. There is an aspect of northern migration of the tree line that will directly affect DND, i.e., the increased risk of forest fires. Future climate warming will result in far more dead and diseased trees ready to fuel fires. Forestry officials state that this is one of the most significant aspects of northern climate migration. As the summer of 1990 in arctic Canada has shown, forest fires in northern regions where communications and infrastructure are poor habitually evolve into situations that are profound disasters partly because of our inability to deal with them. DND has as one of its mandates aid to civil authorities, and as the organization with one of the largest groups of personnel in the North, it is and will continue to be incumbent on the CF to assist in such activities as fire fighting and other environmental disasters. As the risk of severe fire increases over the coming decades, DND policy and logistics may require modification to accommodate the new situation.

Summary

21. The policy aspects of DND operations in the Arctic are very much related to global climate change. It may be that in the future the general level of activity in the North by Canadian society will increase as climate becomes more amenable. New possibilities for economic activity will open up and settlements will be created where they are not currently viable. Because it

is part of our overall formal societal structure, an enhanced DND presence in parallel with this growth would most likely occur. Despite climatic warming, doing business there will become more, not less, expensive. How much we are prepared to pay for new facilities and for remedial measures on existing infrastructure will require considerable thought, as will our defence policy as it pertains to Canadian sovereignty in the North.

ENVIRONMENTALISM AND ENVIRONMENTAL CHANGE AS IT AFFECTS CANADIAN DEFENCE POLICY AND OPERATIONS: PART THREE; ARCTIC ISSUES[1]

INTRODUCTION

1. Some 40% of Canada's landmass is located north of the 60th parallel. This region is surrounded by 2/3 of our coastline and offshore waters, and shares the Arctic Ocean, the world's fourth largest, with seven other countries. It is because of these facts, among others, that the strategic and operational issues related to global climate change as it relates to arctic Canada are of concern to the Department of National Defence (DND). In a policy context, we need to know the security and sovereignty implications of issues such as; the possible melting of sea ice between the Arctic Islands, and the northward shift of forest and tundra. From an operations point-of-view, the practical problems of melting permafrost (perennially frozen ground) that underlies about half of Canada's land surface and significantly changed meteorological conditions, will require modifications to existing infrastructure and revised planning for future construction, materiel and exercises.

2. The initial purpose of this paper, part three in a series of related topics, is to describe in some detail the natural phenomena and ecosystems in arctic Canada that are susceptible to modification from the effects of global warming and the scientific issues as they are perceived by current researchers in the various fields. Much of the work herein consists of a review of pertinent literature on various aspects of the topics chosen, i.e. meteorology, permafrost, sea ice and the tree line. The logic of this approach in a policy-related paper is that readers should be able to have ready access to at least a précis of the basic scientific arguments that are driving the issues being considered.

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[1]. The research for this paper was conducted under ORAE Activity 44107. It is one of a series of papers on the general subject sponsored by CORAE, DG Pol Coord and DG Pol Plan.

3. The political and economic infrastructure of Canada, as in most societies, has developed with an underlying assumption of a variable climatic environment which is stable about a long-term mean. The greenhouse warming of the atmosphere, whatever its magnitude, undermines this assumption, and thus, as well as environmental change, substantial social and economic change will also take place. It is anticipated that over the next half century, virtually that period of time since the end of the Second World War, human activities will have substantially altered global climate by enhancing the earth's natural green house effect. Though there is some disagreement about the range and time frame, a general consensus among climate modellers is that the annual global average temperature will rise from the 1950-80 value of 15.3° C to 16.8-19.8° C by the year 2035 (Tucker, 1989), i.e. approximately 0.3° C per decade. In the Arctic, the warming is anticipated to be less than the global average during the summer, perhaps as little as half a degree. However, during the winter, a dramatic increase in temperature is expected, as much as 8° C according to the Canadian Climate Centre general circulation model (GCM) (Environment Canada, 1989). This would be twice the global average. In addition, rainfall which now falls in southern Canada is expected to shift northward, increasing arctic precipitation by 20-30%.

4. It must be emphasized that at the current state of knowledge, these predictions are speculative at best, perhaps uncertain by a factor of three. More basic research is required before we will be able to understand the driving influences of global climate change in any comprehensive way. According to the editors of Nature (1990):

> What the years ahead will bring is anybody's guess. Much will depend on the degree to which the computer predictions are borne out by measurements of climate on the surface and of the Earth's radiation balance from Earth satellites. But the most important area of relevant research...is the cost of either adaption or avoidance (which) may well amount to a substantial fraction of the world's total stock of social capital.

5. This leads to the second purpose of the study which is to relate the diverse changes that might occur in the North within the next fifty years to

possible future policy and operations for DND. It is current policy that the Canadian Forces (CF) be able to operate anywhere within Canadian jurisdictional limits, including the Arctic (Department of National Defence, 1987); and in the view of a former Chief of the Defence Staff, one could assume that as the political situation in Europe evolves, more resources may be available to enhance our ability to deploy in Canadian territory and to be physically capable of a reasonable presence throughout Canadian 'geography' (Thériault, 1990). There will certainly be financial and social costs involved in these operations, and if we are able to mitigate their effects on the Department to any extent by long range planning, the savings should be significant.

METEOROLOGICAL CONDITIONS

6. Because virtually every operation carried out by DND in the North is influenced to a greater or lesser degree by the 'weather', it is considered useful for purposes of context to spend some time describing the existing climate of Arctic Canada. Also, it is difficult to imagine what a scenario 50 years from now might be like without a baseline of sorts. Most of the following information has been condensed from an encyclopedic Environment Canada publication edited by J.B. Maxwell (1980). Considerably more detail may be gleaned directly from the source document.

Temperature

7. One of the most profound features of temperature in the Canadian Arctic Islands is the temperature inversion which can be found throughout the year. This aspect is distinct to polar regions where the extreme regime of continuous day and night, high albedo, and low solar angle bring about a negative radiation balance over the snow and ice surfaces during much of the year. In general, a deep intense surface inversion dominates in winter (November to April), while in summer, the inversion is weaker and the base is more frequently above the land. Surface winds and terrain elevation, aspect, and vegetation are all important factors affecting the phenomenon, with the result that the lowest winter temperatures occur in snow-covered, non-

vegetated hollows while the highest winter temperatures occur in open windy areas or on sloping ground.

8. An examination of the annual temperature regimes reveals several important facts. Firstly, the lowest mean temperatures occur in February rather than January as in the case of the more southerly locations. In the Arctic, the occurrence of polar night means that it is not until February that the sun's rays provide enough warmth to check the declining temperatures. Secondly, on a monthly or annual basis the Arctic Islands are the coldest regions of Canada (Fig.1). At both Eureka and Cape Dyer, for example, only three months have monthly mean temperatures above freezing whereas at Toronto only four months are below freezing (Maxwell, 1980). Finally, extreme occurrences are generally not as prevalent in the Arctic as further south.

9. In general, the beginning of the winter season, defined as mean daily temperature $\leq 0^\circ$ C, varies from August 20 in the extreme north to September 25 near Hudson Strait. Mean daily minima below -40° C, however, do occur in the Arctic Islands and it is probable that at many inland, low-level, sheltered locations values are even lower. By May, approximately a 20° C modification of winter conditions has occurred, but the seas and channels are still mostly ice covered.

10. The warmest month of the year in the Canadian Arctic Islands is July with mean daily maxima near 10° C along the mainland and southern coasts and near 5° C along the more northern island coasts. Sheltered inland sites may be perhaps 5° C higher. Over the larger water bodies, the air temperatures are closely related to water temperatures and in July are close to 2.5° C. Daily ranges in the order of $4-5^\circ$ C are typical in such areas. Perhaps the most striking feature of the summer situation is the small range across the whole region. With the onset of cold weather in late August and early September, the summer uniformity of temperature breaks down and winter conditions prevail over most of the region by mid-October. In those areas where open water

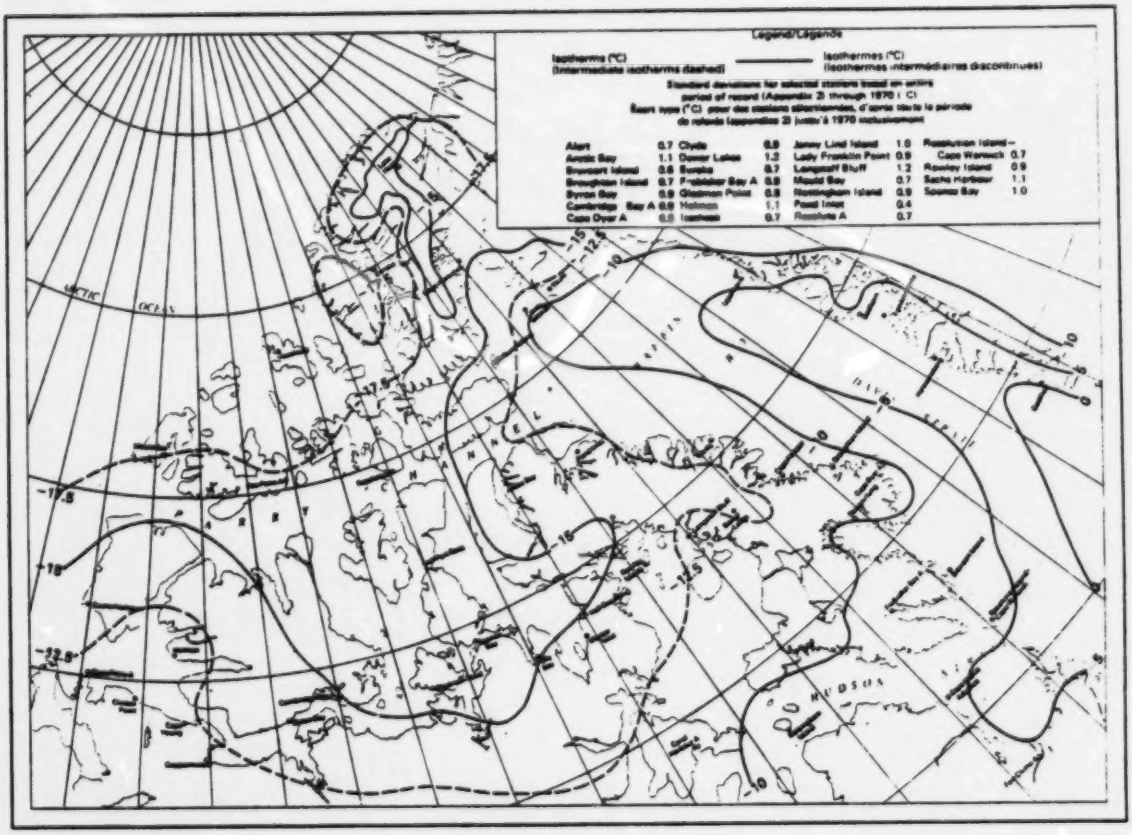


Figure 1. Mean daily temperatures (Maxwell, 1980).

exists into November and December, winter may be somewhat delayed.

Precipitation

11. Basically, the amount of precipitation over any area depends on the moisture content of the air, the pattern of weather systems affecting the area, and the presence of terrain effects whether acting alone or in combination with some weather system. These influences result in generally low annual precipitation amounts among the Canadian Arctic Islands with the result that much of the region is classified as 'polar desert'. Annual precipitation amounts range from less than 60 mm in the Eureka area to near 700 mm in the vicinity of Cape Dyer (Fig. 2).

12. Large variations in precipitation amounts occur from year to year, a typical characteristic of desert climates. They are caused by changes in the frequency and position of storm tracks and in the degree of storm penetration into the Arctic. Heavy precipitation in the Arctic Islands is unusual, particularly in winter when seas are ice-covered and open water as a source of atmospheric moisture is distant, and when most migrating low pressure areas which do enter the area are occluded, having deposited their water content elsewhere.

Cloud Cover

13. The chief determining factors for the distribution of cloud cover over the Canadian Arctic Islands include frontal activity and cyclonic systems, the amount of open water, inversion structure, air temperature relative to the water, and such local effects as onshore winds and orographic uplift. The first of these factors is most important for middle and high cloud development while the other factors are mainly related to low cloud. The large role that the latter factors play in the Arctic Islands is reflected in the very great amounts of low stratus clouds which exist there in the summer and autumn, particularly in the coastal and oceanic regions.

14. In general, the distribution of mean cloud amount by month shows a minimum of three to five tenths cover in winter with a fairly sharp increase

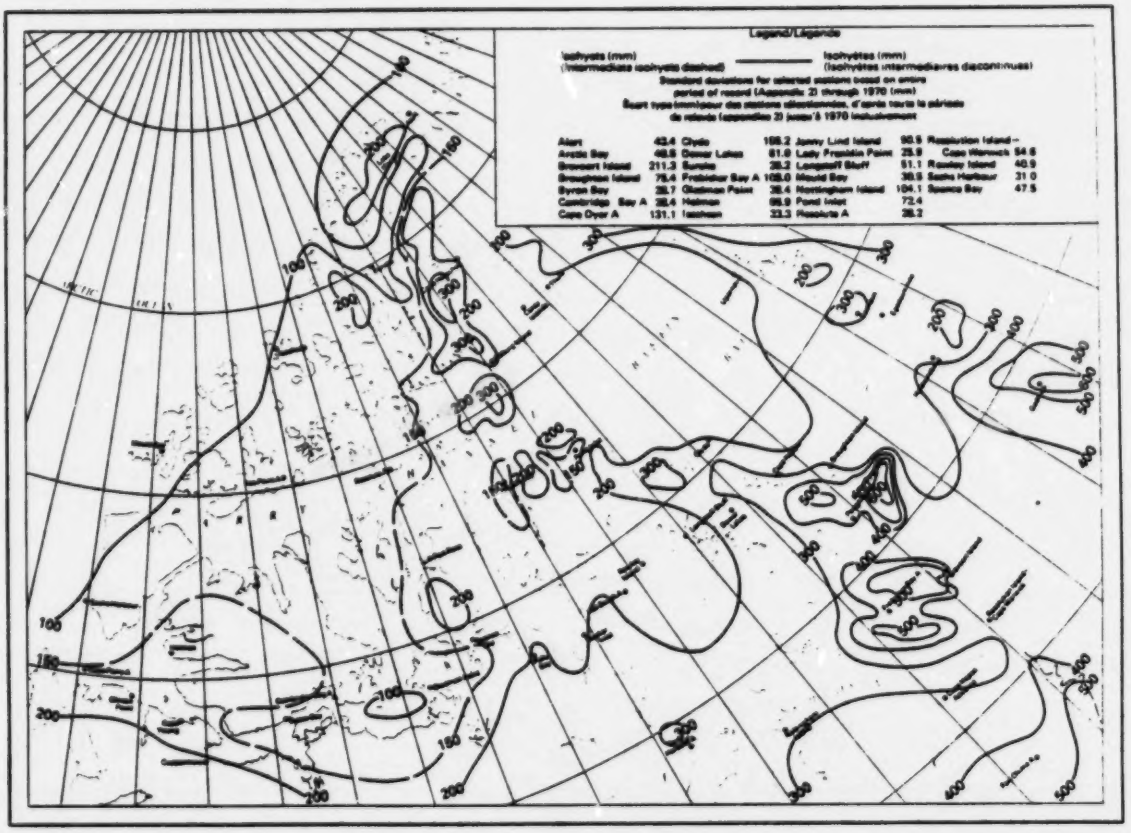


Figure 2. Mean Annual Precipitation (Maxwell, 1980).

during April - May, to a secondary maximum in June of seven to eight tenths. The primary maximum of eight to nine tenths occurs in September and is related to the maximum of cyclonic activity at that time. Thereafter, the mean cloud amount drops sharply back to the winter minimum. This pattern is fairly typical of a maritime cloud regime in which sea ice is a factor.

Operational Aspects of Meteorological Conditions

15. Numerous aspects of weather have a profound effect on DND operations carried out in the North. Today, air groups are the most affected, though in the future it may be sea exercises that are prominent, as will be discussed in the following section of this report. In dealing with many of the meteorological phenomena discussed above, contradictory situations are encountered. For example, with air masses relatively free from pollutants and in the presence of cold, clear isothermal conditions, visibility in the Arctic is exceptionally high. Despite the Arctic Haze phenomenon, distant objects stand out with great clarity. Conversely, with persistent low cloud or fog, or with falling precipitation, blowing snow, or suspended ice crystals present, visibility is severely reduced and can remain so for extended periods of time. Such conditions can significantly curtail aviation operations and land and sea transport. Regardless of their effect on visibility, obstructions to vision can be important in themselves - for example, blowing snow is a factor to be considered in the clarity of radio communications (Maxwell, 1980).

A. Obstructions to Vision

16. Blowing snow is a major phenomenon in the Arctic Islands from October to May, during which time it is the chief restriction to visibility. In general the snow particles carried by the wind may come directly from precipitation falling during a storm or they may be picked up from the surface by gusts. Even low wind speeds will be sufficient for blowing snow in the former case, but in the latter, very strong winds may be necessary. Blowing snow has become more and more an important design consideration. This is particularly true in the increased use of aero-derived gas turbine engines in stationary

applications such as power generators, especially in northern latitudes (Maxwell, 1980).

17. Fog and low clouds continually threaten aircraft operations over the area in summer and, as a navigational hazard to sea operations, fog is second only to sea ice. During the June-to-September period, advection-type sea fog is the most common obstruction to vision over the arctic waterways and it is during this time that the worst flying conditions occur. This dangerous formation occurs when a relatively warm air mass with a sufficiently long trajectory over exposed water areas or moist ground surface moves over colder water or drifting sea ice. The initial evaporation from the moist surfaces produces a low-level cooling in the air mass and the resulting temperature inversion inhibits turbulent mixing with the drier air aloft. When the moist air below the inversion then moves over the colder water or ice, the excess moisture condenses to form fog or mist. Fog may also be formed in this moist air when it is subjected to adiabatic cooling by being lifted along the shore of an island. The result of the above processes is a fairly widespread fog cover over the seas when the ice is melting and along islands coasts where onshore winds prevail. Such coastal fog would usually extend a few kilometres inland. On the other hand, cross-channel and offshore winds tend to work against this type of fog development. Strong winds also work against advection fog, tending to lift it to form low-lying clouds.

18. As the summer season advances, particularly over the seas the fog becomes more patchy. It will, however, persist to some degree until freeze-up with the result that north of the Parry Channel, fog is infrequent from mid-September on, but is still in evidence through October over southern Baffin Island. Meanwhile, conditions become increasingly favourable for the development of steam fog (arctic sea smoke) from early October on. This forms when very cold air passes over areas of open water. As the capacity of the air to hold moisture is restricted by its low temperature and the rate of evaporation from the water surface remains relatively high, the excess moisture now in the air quickly condenses to form fog. Steam fog can at times be very extensive and can be blown over a nearby coastal station if the wind

is in the right direction; however, in winter, it is relatively infrequent over much of the Arctic Islands area, with leads of open water being of generally small extent. Exceptions are in the vicinity of Jones Sound, Barrow Strait, Lancaster Sound, north Baffin Bay, and Hudson Strait where some open water may usually be found throughout the winter.

19. Ice fog is observed relatively infrequently outside of the settlements in the Canadian Arctic Islands due to the lack of moisture in the very cold air. It can occur naturally in uninhabited areas when the temperature falls below -40° C, but where human activity exists, the water vapour from vehicle exhausts, domestic heating, and power plants enhances its formation at temperatures below -30° C. The winter inversion is an important factor in the persistence of ice fog once it is formed; on the other hand, increasing temperatures or wind speeds will tend to dissipate it.

20. Ice crystals are a common sight in arctic regions. They are formed by the sublimation of water vapour at low temperatures and can fall from cloud or a cloudless sky. An ice crystal haze may be formed which can cover an extensive area both horizontally and vertically, but the associated horizontal visibility is seldom reduced below 3 to 8 km and the vertical visibility is little affected. Despite the frequency with which ice crystals are recorded, they probably represent an insignificant part of the measurable precipitation water equivalent (Jackson, 1959).

B. Structural and Aircraft Icing

21. The hulls and superstructures of ships or marine installations may experience two main types of icing at sea. Icing from fresh water may be the result of freezing rain or occasionally wet snow followed by a drop in temperature. At present, only in the waters adjacent to Brevoort and Resolution Islands is this type of icing a significant hazard, and then only in the fall and spring. Structural icing from sea water is generally regarded as the most frequent form and it is probably the most dangerous because of the rapid rate at which it can accumulate. It occurs whenever sea spray is

present in combination with an air temperature below the freezing point of sea water (~-2° C).

22. In terms of aircraft operations, icing can be a significant hazard. Ice accumulation on the airframe can distort the smooth flow of air causing reduced lift and increased weight, drag, and stalling speed. Although most modern aircraft have a sufficient reserve of power to carry heavy loads of ice, the ice tends to increase fuel consumption and reduce range.

23. Before ice will form on an aircraft, two conditions must be met: the aircraft skin temperature must be below 0° C and a supply of supercooled water droplets must exist. The variation of icing probability during the year is similar to the variation of total cloud amount in that the lowest values occur in winter (January, February) and the highest in autumn (October) and then in spring (May). The minimum probabilities of winter are, of course, related to the season's low temperatures and low water content of the air. Occasionally, penetrations of warmer, moist maritime air (particularly in the eastern Arctic) will produce more favourable icing conditions. In the autumn, the risk of icing is greatest as that is the time of year of the coincidence of maximum storminess and open water, and when air temperatures generally drop below 0° C. The secondary icing maximum of spring is related to the secondary maximum of storminess occurring in that season.

24. In addition to being a hazard to aircraft, icing also affects ground-based structures (both land and marine) and vehicles in the same forms as those outlined above. Favoured geographical areas for such surface icing include mountainous coastal areas near open water with frequent onshore wind conditions and near open water at high latitudes in autumn and winter where arctic sea smoke is highly charged with supercooled water droplets.

C. Turbulence

25. The term turbulence in meteorology normally refers to atmospheric motions on a smaller scale than that of the mean flow. Four main types of turbulence which are of importance to the safety of aircraft may be

distinguished: convective turbulence, mechanical turbulence, turbulence in mountain waves, and high-level clear air turbulence (CAT).

26. Work in the lower 2 to 3 km of the troposphere over the central Arctic Ocean (Kovrova, 1968) indicates that there is well-marked turbulence (of the convective and mechanical types) in clouds of the central arctic regions during the summer. The turbulence was particularly noticeable in fog and in low stratus clouds at heights of 100 to 200 m. In all cloud types examined, it intensified sharply at the upper cloud limits, but the strengthening was not always as well-marked at the cloud base.

27. Greenaway (1950) noted that turbulence is never as severe in the high latitudes as it is in southern Canada. It is seldom encountered in the summer except when passing through a front, or at low latitudes over the barren lands. It is more common during late fall and winter, but only when flying over large open-water leads within the ice zone. From casual observations it would appear that when an open water area is sufficiently large to influence the air above it and temperatures are low, turbulence may be expected to a considerable altitude. These areas are generally covered by a broken layer of stratocumulus above which the air is smooth. Though the general topic of sea ice is to be discussed later in this paper, it is pertinent to note that climate modellers are predicting enhanced areas of open water with future global warming. This will likely increase the degree of air turbulence encountered in arctic air operations.

Discussion

28. In summary, it is reasonable to expect that future meteorological conditions in arctic Canada may be more difficult to deal with, despite a considerable amelioration from those existing today. Climate modellers expect the North to be as much as 8°C warmer than today, though the global predicted average rise is 1.5-4.5° C with a best guess at a high level of confidence of 2.5° C by mid-century (Tucker, 1989). A portion of the increase in high latitude temperature will be a result of increased latent heat release from moisture derived in the tropics.

29. Though regional details are poorly understood, climate model predictions also hold that there will be increases in arctic precipitation throughout the year. According to Manabe and Stouffer (1980), for example, summer precipitation may increase by 10-50% in summer and by up to 60% in winter. These findings while higher in range, are compatible in direction with those of the Canadian Climate Centre (see para. 3). The interactions between temperature and precipitation in models of arctic climate are not particularly straightforward or highly reliable. As a generalization, increased rainfall in any area would tend to enhance evaporation rates and cloud cover which would reduce insolation and ground surface temperatures, thus resulting in negative feedback to a rise in mean annual surface temperature. A decrease in mean annual summer rainfall would lead to drier conditions, reducing the evaporation rate and causing the soil to warm. This process would feed back positively on climatic warming (Goodwin et al., 1984).

30. In essence, we can expect a much warmer, wetter Arctic with far more unsettled meteorological conditions 50 years from now. Coastal areas will be significantly foggier because of increased open water conditions (to be discussed in later sections), and increased overall moisture. For the similar reasons, one can expect increased low stratus cloud cover in summer.

31. As a result, the requirements for DND aviation meteorological services are likely to increase in the coming decades. Present DND missions in the North include interception of aircraft and airborne vehicles, surveillance/sovereignty, search and rescue, and tactical and logistical air support for land force exercises. With climatic amelioration, many of these roles could conceivably increase in the future. Similarly, as will be discussed in the following section, if DND activity increases in arctic waters, because of expanded commercial shipping in the North, marine forecast services will also need to be bolstered to be better able to predict events such as coastal fogs, ice conditions and sea states, etc.

32. In both cases, new technologies will be required to aid forecasting. The areal coverage of weather observations 'north of 60' already falls well short of the World Meteorological Office recommended 150 km grid (DND, 1988). To remedy this, automatic weather stations, ground-based radar coverage and enhanced satellite surveillance and communications would need to be considered. There will be increasing need for an expanded military meteorological presence in the Arctic. Careful consideration will probably be given to its equipment, location and its association with Atmospheric Environment Services as their services are enhanced in the North. Similarly, the effects of changed meteorological conditions on the efficiency of the North Warning System radars will have to be assessed.

SEA ICE

33. Sea ice and extreme winter cold have been traditional obstacles to shipping and the development of resources in Canada's north. In the past several decades, as the search for offshore hydrocarbon resources and minerals has intensified, the operational and strategic implications of navigation through and within the waters of the Canadian Arctic Archipelago have been brought to the forefront. Not only are there the practical aspects of year-round navigation in ice-choked waters to consider, but there are sovereignty issues associated with foreign nationals navigating through Canada's 'internal waters' of the Northwest Passage.

34. Sea ice limits have long been observed by ships and at coastal locations. Historical records have been used as climatic indicators by Lamb (1977) and others, although the early observations present many problems of interpretation (Barry, 1986). Ice conditions are now reported regularly in the marine synoptic observations, by aerial reconnaissance flights, and coastal radar. Since the early 1970s, satellite remote sensing data, particularly the American National Oceanic and Atmospheric Administration's (NOAA) Very High Resolution Radiometer and Nimbus passive microwave data, have been routinely incorporated into the US Navy-NOAA Joint Ice Center weekly ice charts for the northern and southern hemispheres. Maps of sea ice generally

depict the boundaries for various ice concentration classes (0-10/10), and distinguish age categories and the degree of ridging intensity.

35. Sea ice is one of the most visible phenomena of climate within the Canadian Arctic Islands and it dominates the marine environment for 9 to 12 months of the year depending on the particular geographical location. Not only are the patterns of freeze-up, growth, extent, decay, and break-up important, but characteristic of the ice itself such as surface roughness, lifting force (due to changing water levels), bearing capacity, and pressure must be considered (Barry, 1990). Such features are significant for the design and operation of any marine installations (such as piers or drilling platforms), vessels, or for other scientific or industrial activities that may require the use of a sea ice covered area (eg. the winter highway from Inuvik to Tuktoyaktuk on the Beaufort Sea, or aircraft landing strips on Canadian and Soviet ice islands).

36. In addition to these aspects, sea ice is an important component in the highly interactive global climate system, reflecting and influencing conditions in the atmosphere and oceans. The presence of sea ice restricts exchanges of heat, mass, momentum and chemical constituents between ocean and atmosphere, reduces the amount of solar radiation absorbed by the Earth's surface, and affects oceanic and atmospheric circulation patterns. Changes in arctic sea ice can be considered both an effect and a cause of climate change.

37. Although typically overlying 7% of the world's oceans, sea ice cover experiences considerable seasonal variability. Because of increased reflectivity of ice compared to open water, cold years which create greater amounts of ice tend to perpetuate themselves. In the Northern Hemisphere (Fig. 3), the total extent of sea ice varies from a minimum of 7.8×10^6 km^2 in September to a maximum of about 14.8×10^6 km^2 in March (Parkinson et al., 1987). Any reduction in sea ice cover brought about by climate change would have significant impacts on both the planning and operations of DND in the North. Recently, Wadhams (1990) noted a significant thinning of sea ice over a 300,000 km^2 area of the Arctic Ocean. McLaren et al. (1990) countered that

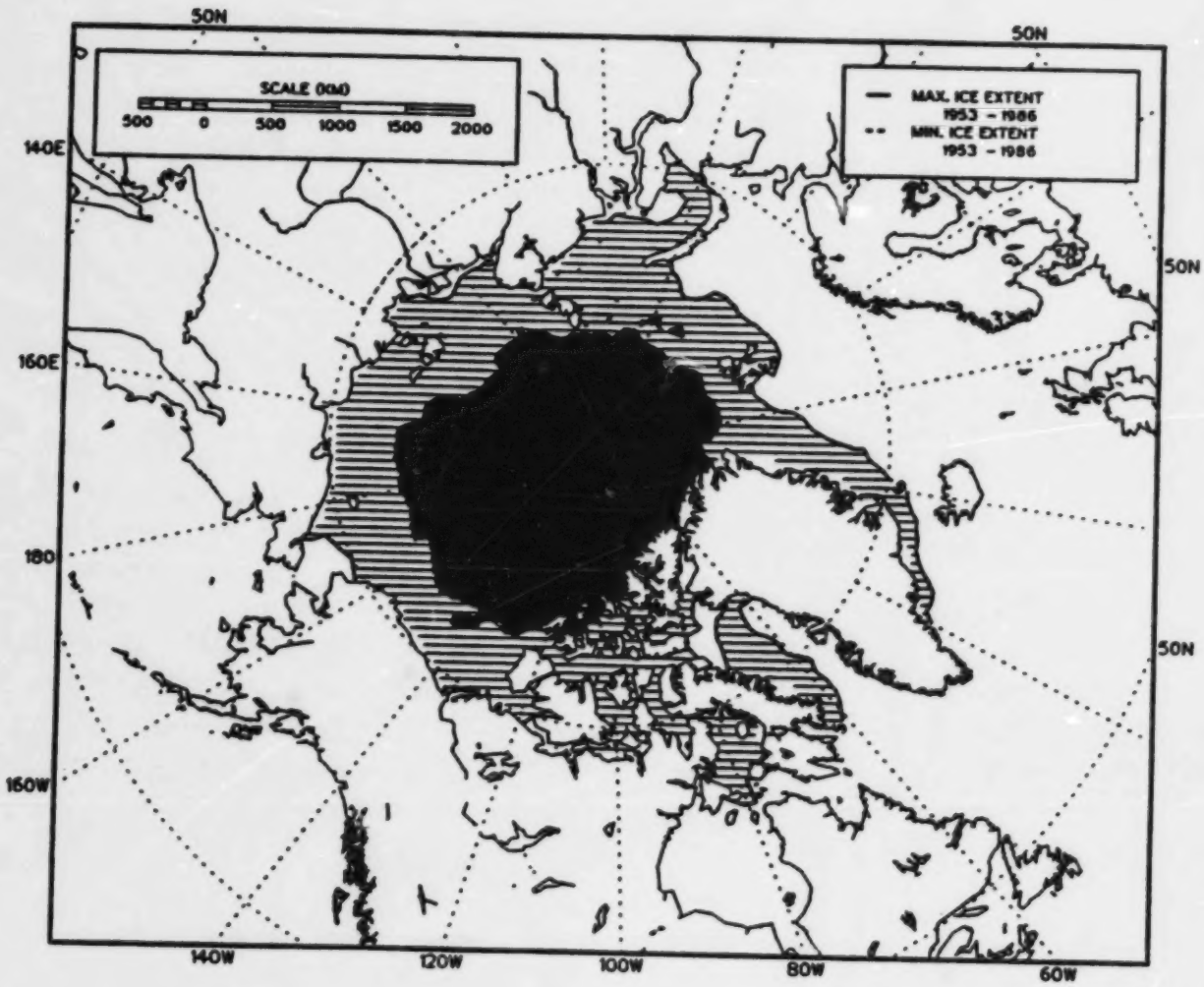


Figure 3. Sea ice distribution (Agnew, 1990).

no data published to date can provide a reliable indication of whether the sea ice in the Arctic Basin is thinning, thickening or remaining essentially constant. Therefore, before assuming any future policy and operational changes that might be required by DND, it would be prudent to assess the current state of agreement on ice conditions as far as the scientific community is concerned.

Ice Extent

38. Seasonal changes in sea ice cover over the hemisphere are, in essence, a response to large scale radiational forcing. Once sea ice cover is established or has been removed from the ocean surface, changes in the atmosphere/ocean interface cause feedbacks on the hemispheric, regional, and local scale which further modify the climate. These feedbacks increase the complexity of the sea ice /climate system and, thus, complicate cause-effect relationships. Walsh and Johnson (1979) have statistically analyzed the relationship between sea ice and atmospheric circulation in an attempt to delineate these effects and found differences between the sea ice growth season (late August to late January) and sea ice retreat season (late February to July). These results have been qualitatively evaluated by Agnew (1990) partly to demonstrate that a comprehensive sea ice data-base now exists at the Canadian Climate Centre which can be used for regional studies.

39. Agnew concluded that during ice retreat, the response of the sea ice to prior atmospheric forcing was stronger than the response of the atmosphere to the prior distribution of sea ice. During the growth season, the reaction of the atmosphere to the sea ice was slightly greater than the reaction of the sea ice to the atmosphere. At the time of minimum ice (end of August), sea ice has receded from most coastal areas and covers only a portion of the Arctic Basin. During the ice growth period, the distribution of land mass around the Northern Hemisphere restricts the expansion of sea ice in many longitudinal sectors, e.g. the Canadian Arctic Archipelago.

40. Unrestricted longitudinal expansion of sea ice extent occurs: between 160W to 180W longitude in the Bering Sea/Chukchi Sea, between 50W and 70W

longitude in the Baffin Bay/Davis Strait/Labrador Sea area, and between 40E to 40W longitude in the Barents and East Greenland Sea. Hudson Bay/Foxe Basin (between 75W and 90W longitude) also shows a considerable variation between maximum ice cover. This sector is eventually restricted in its growth by land to the south. The Baffin Bay/Davis Strait/Labrador Sea region of eastern Canada has the largest variation in sea ice extent in the northern hemisphere. Over one sea ice growth/melt cycle, ice cover extends down the full length of Eastern Canada from northern Baffin Bay to Newfoundland, a distance of over 2500 km. In general, the region between minimum and maximum ice cover is referred to as the seasonal sea ice zone.

41. According to Agnew (1990), the monthly mean sea ice charts also show well defined patterns of ice breakup in the Canadian Arctic Islands, Baffin Bay and Hudson Bay. The records suggest that sea ice breakup does not proceed from southern portions of the Canadian Arctic northward, but takes place simultaneously along the northwestern coast of Hudson Bay, northern Baffin Bay, and interior channels of the central Canadian Archipelago. These centres of ice disintegration expand as general breakup progresses. By the end of June in Hudson Bay, open water covers a large portion of the northern, eastern, and western portions of the Bay with complete sea ice cover still remaining in the south-central part. This pattern of ice breakup is attributed by Agnew to the counterclockwise currents in the Bay which accumulate ice in this region.

42. Baffin Bay sea ice breakup proceeds from the northwest as an extension of the North Water Polynya and continues down to the northern coast of Baffin Island. Warmer water of the West Greenland Current simultaneously helps breakup ice in eastern Baffin Bay so that the west coast of Greenland has open water much earlier than the east coast of Baffin Island where the cold Canada Current maintains the sea ice. According to Agnew, this pattern of breakup is due to the counterclockwise currents in Baffin Bay/Davis Strait. Sea ice tends to persist along the north coast of Baffin Island well into July.

43. The extent of the ice can vary substantially from year to year. Using arctic data from 1968 to 1976, Kukla (1978) found a substantial increase in ice coverage between 1971 and 1973 followed by a gradual decrease through 1975. In their more extensive study, Walsh and Johnson (1979) concluded that the average extent of arctic ice has generally increased over the last 25 years. This trend seems to agree with decreases in arctic surface temperatures between data, though further research is required to assess these findings in light of current predictions of global climate warming.

Sea Ice Dynamics

44. It is important that sea ice dynamics be well understood if general circulation models (GCMs) are to be better predictors of future climate. Hibler (1980), for example, states that the primary mechanisms suggested for the variation in the extent of ice on the Greenland Sea have been atmospheric wind and temperature and oceanic heat transport, one of the least understood mechanisms in global climate change models. The primary factor responsible for year to year variations is northward oceanic heat transport. However, for short-term (over a month or so) variations, wind and temperature effects appear critical. Anti-correlations (i.e., one region receding while another expands) may be due to the development of certain long-wave patterns in the upper level westerly winds. According to Agnew (1990), this type of explanation has also been advanced by Kelly (1978), who suggests that eastern arctic ice extent may correlate with the position of the Icelandic low pressure system.

45. Mysak and Manak (1989) have studied seasonal and interannual extent and variability of arctic sea ice, in their case over a 32 year period from 1953-84. They found that the smoothed anomaly fluctuations of ice coverage varies from a 4-6 year cycle in the western Arctic to a decadal one for the eastern Arctic. In agreement with earlier studies, there was a significant out-of-phase relationship between the 25 month smoothed anomalies in the Chukchi/Beaufort Sea region and western Greenland. They proposed that this behaviour is related to atmospheric pressure anomalies associated with a

variation in winter air temperature between northern Europe and western Greenland.

46. Another aspect of the ice extent is the degree of temporal persistence. To examine this effect, Lemke et al. (1980) divided ice coverage data into 36 equal longitudinal segments, and analyzed monthly data over the 11-yr period between January 1966 and December 1976. In these data the strongest annual changes in extent were found in the regions west and east of Greenland while the smallest changes were found in the Beaufort Sea.

47. The general pattern of the ice cover circulation in the Arctic Basin has been known for some time. It consists of a gyre in the Beaufort Sea and a cross-polar current known as the Transpolar Drift Stream (Fig. 4). It carries ice from the East Siberian Sea and the Bering Strait, passing it across the North Pole and down the east coast of Greenland. Because of the recirculating character of the Beaufort Gyre, it is possible for ice that survives the summer melt to stay in the Gyre for a large number of years. Consequently, some of the thickest multiyear ice is found in this region, and it one of the reasons that the Soviet Union has located many of its drifting ice stations here.

48. Drifting ice stations in the Arctic typically have been found to move at a rate of about 6 km per day, but drift rates can be highly variable. One-day drifts of over 20 km have been observed (Hibler, 1980). It is also possible for the ice to remain effectively motionless for several weeks. However, except for ice very near shore, this motionless behaviour appears to be the exception rather than the rule. Due to almost constant motion, formation, and decay, sea ice has a highly variable thickness, which is significantly affected by the amount of ridging. The thin ice plays a particularly important role in ice dynamics because of its low strength and high growth rates.

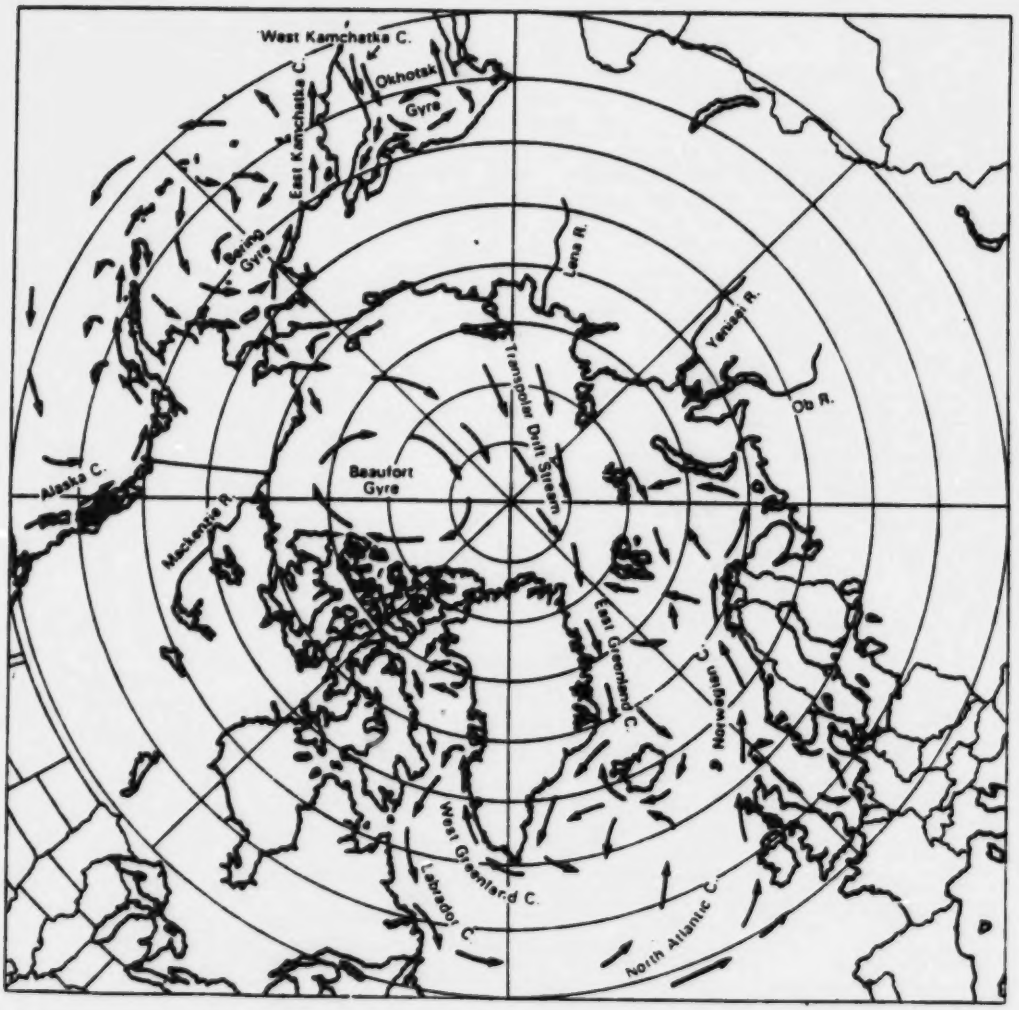


Figure 4. Sea ice circulation (Parkinson et al., 1987).

Numerical Simulations

49. While much research is being done on predicting sea ice growth and decay from observations of existing seasonal conditions, a more theoretical approach of modelling conditions by numerical simulations is gaining widespread support. A class of model studies particularly relevant to this review are numerical simulations of spatially varying sea ice growth, drift, and decay over at least one seasonal cycle. Simulations of this nature have been performed both using observed input data (Washington et al. ,1980; Parkinson and Washington, 1979 and Hibler, 1979) and as part of a global coupled atmosphere ocean model (Bryan and Lewis, 1979, and Manabe et al., 1979). Except for the simulation by Hibler (1979), however, these studies have been essentially thermodynamic in nature and include only simple parameterizations of ice motion.

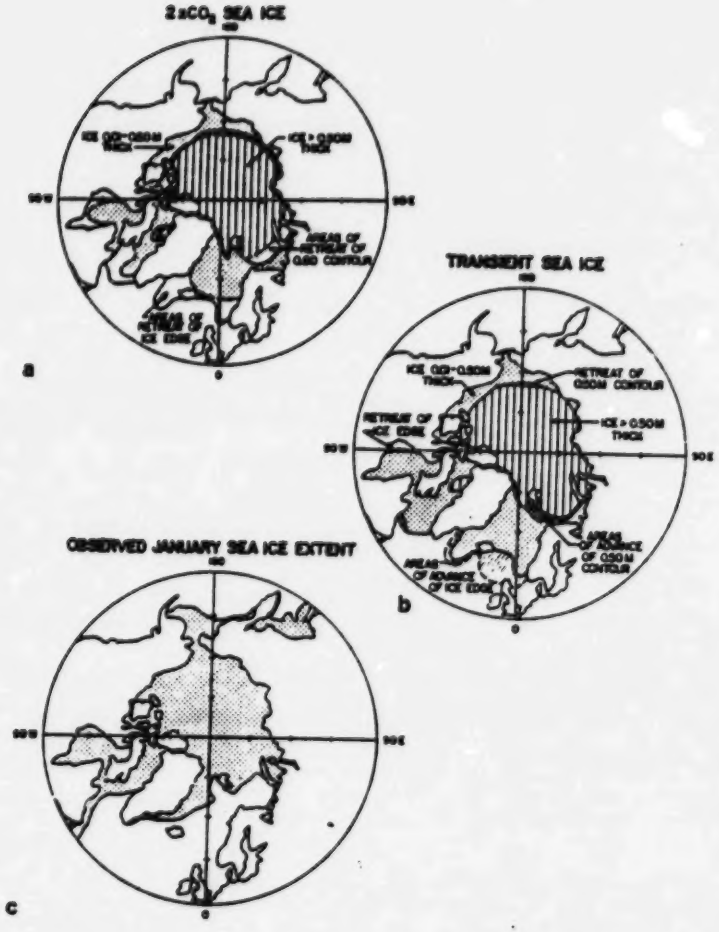
50. Walsh (1983) has summarized the results of Parkinson and Kellog (1979) who have performed a set of simulations of sea ice. While their model does not incorporate sea ice dynamics or feedback to the atmosphere, it does contain a state-of-the art treatment of sea ice thermodynamics, i.e. the effects of leads and snow cover are computed by the model. Parkinson and Kellog find that a temporally and spatially invariant warming of 5^0 C (accompanied by a modest prescribed increase in cloud cover and the upward oceanic heat flux) would completely melt the ice cover during summer in each hemisphere. The ice does reappear during winter in the simulations. In a more complete model experiment, Manabe and Stouffer (1980) have performed a series of coupled ice-ocean-atmosphere simulations in which the CO_2 concentrations corresponded to the present (1 X CO_2) and to a quadrupled amount (4 X CO_2). The ocean model consisted of only a mixed layer with no currents and sea ice was represented as a motionless slab without leads. Salinity effects were not included in either the sea ice or the ocean model. It should be noted that the control experiment (1 X CO_2) produced a winter-time ice cover that is approximately twice as extensive as observed in the Arctic.

51. When the CO_2 concentrations were quadrupled, the ice disappeared completely from the Arctic for several summer months each year. The near-surface changes in the central Arctic were ~ 13° C in winter and ~ 4° C in summer. Reasons given by Parkinson and Kellog (1979) for greater warming in high latitudes are: albedo-temperature feedback resulting from the enhanced melting of snow and ice; an increase in the atmospheric moisture content and the latent heat transport into high latitudes; and, strong stability and lower tropopause of the polar atmosphere. Interestingly, according to Walsh (1983), Soviet investigators have found that observed ice anomalies on the interannual time-scale are more highly correlated with warm-season temperature anomalies than with cold-season temperature anomalies.

52. Washington and Meehl (1989) have generated revised iterations of their global climate model that have a new approach for sea ice conditions. Three simulations were run: one with an instantaneous doubling of atmospheric CO_2 (from 330 to 660 ppm), another with the CO_2 concentration starting at 330 ppm and increasing linearly at a rate of 1% per year, and a third with CO_2 held constant at 330 ppm. Results at the end of 30 years of simulation indicate a globally averaged surface air temperature increase of 1.6° C for the instantaneous doubling case and 0.7° C for the transient forcing case.

53. When CO_2 is doubled, reductions of sea ice occur almost everywhere (Fig.5). Near the ice margin, a mean reduction of ice thickness is represented by periods of open water alternating with periods of ice-covered water. Therefore, the frequency of ice-free ocean areas increases and is evidenced by a decease of seasonal mean ice thickness. In the transient case, the largest areas of sea ice decrease from the warmer climate occur mainly in Hudson Bay and are associated with the warmer continent. In the North Atlantic, the sea ice limit advances in association with the colder temperatures.

54. Washington and Meehl note that sea level pressure (SLP) differences affect atmospheric circulation in these model experiments. For their $2xCO_2$ case, the warmer continents in the Northern Hemisphere are associated with



Sea-ice distribution for (a) $2 \times CO_2$ case compared to control case (DJF), (b) transient case compared to control case (DJF), and c observed sea-ice limits for January from Parkinson et al. (1987) averaged over 1973–1976. In a and b *solid contours* indicate control case; *dashed contours* indicate increased CO_2 cases

Figure 5. Future sea ice distribution (Washington and Meehl, 1989).

lower SLP, i.e. negative differences. Large centres of positive differences are located near northeastern Greenland and over the North Atlantic. These are associated with a weakening and northwestward shift of the Icelandic low. Generally, the low weakens, implying fewer and less intense storms, which is partly due to an overall warming of the North American continent and a reduction of baroclinity in this region. The center of the low shifts northwestward over the more frequent ice-free ocean areas of Hudson Bay and the Labrador Sea southeast of Baffin Island. In the North Pacific, the Aleutian low shifts northwestward as the sea ice is reduced north of the Bering Strait. This is manifested by positive SLP in the Gulf of Alaska and negative differences over the northwest Pacific. Lower SLP is located north of the USSR and is associated with the reduction of mean sea ice thickness (and associated increase in episodes of open water) in those regions. Depending on the model and associated circulation regimes, decreases in sea ice often are associated with lower SLP (Mitchell and Hills, 1986).

55. Walsh (1983) concludes that on longer time-scales, where the evidence becomes tenuous, model experiments such as those summarized above (and other qualitative arguments) suggest that sea ice may play a key role in climatic change, especially in the CO_2 context. However, deficiencies in present models of the ice-ocean-atmosphere system are sufficiently serious that model-based conclusions are not yet reliable. Regardless, he states:

> Numerical models, nevertheless, offer unique opportunities with regard to controlled experiments, which can isolate the effects of various components and processes within the complex system of large-scale interactions. Controlled model experiments may well represent the most economical approach to an understanding of the climatic roles of substances such as sea ice. In view of the reliance that is likely to be placed on model experiments in the future, more realistic treatments of sea ice in model simulations of climate seem to deserve high priority.

Paleoclimatic Analogues

56. Given the difficulty that numerical modellers have in detailing future ice dynamics, another approach that is worthy of consideration as a predictive tool is examining the past climatic record. From archaeological, geological and historical records (paleoclimatic research), we are aware of the Viking

voyages to southern Labrador and northern Newfoundland and their subsequent abandonment because of climatic deterioration and expanded sea ice. Intricate studies of events occurring over even greater time spans have shown significant relevance to future scenarios of ice extent and circulation in the Arctic Basin as they might exist during the next century.

57. Dyke and Morris (1989) have been able to describe a model that may have particular relevance for arctic sea ice in the next century. They collected and radiocarbon dated bowhead whale skeletons, species that today are segregated as two separate east and west arctic species because of ice cover, and related them to contemporary ice extent, ocean circulation and the isostatic/eustatic situation. The authors summarized that:

> During the...(final phases of the latest continental glaciation, the Wisconsinan, until the early part of the post-glacial maximum warming, the Hypsithermal)... (11-8.5 ka BP), the inter-island channels of the Canadian Arctic Archipelago progressively became free of glacier ice, shelf ice, and/or sea ice. Bowhead whales occupied areas beyond their present range and, after deglaciation of Lancaster Sound (9.8 ka BP), likely extended during summers from Beaufort Sea to Baffin Bay. Driftwood was not able to penetrate these same channels during this interval, probably due to a meltwater driven oceanographic circulation pattern that produced continuous summer outflow from the channels, preventing entry of driftwood while exporting sea ice.
>
> Starting abruptly at 8.5 ka BP in the central Arctic and extending to 5 ka BP, bowheads were excluded from the channels but driftwood arrived in the same area and apparently throughout the Queen Elizabeth Islands as well. The cause of both these changes was establishment of an oceanographic circulation pattern similar to that at present. In the central Arctic this caused an increase in summer sea ice, sufficient to exclude the whales but moving sufficiently to carry driftwood. The diminished extent of seasonally open water caused a decrease in nourishment of glaciers and an increase in clear weather during the summer. At 5.0 ka BP the bowheads again expanded their summer range into the central Arctic channels but apparently not in as great an abundance as during the early Holocene. Driftwood continued to arrive but with increased frequency, as it did in the Queen Elizabeth Islands.

58. Because there is no reason to infer a change in oceanographic circulation pattern at 5.0 ka BP, it is concluded by the authors that the more favourable sea ice conditions resulted from warmer summers (Fig. 6).

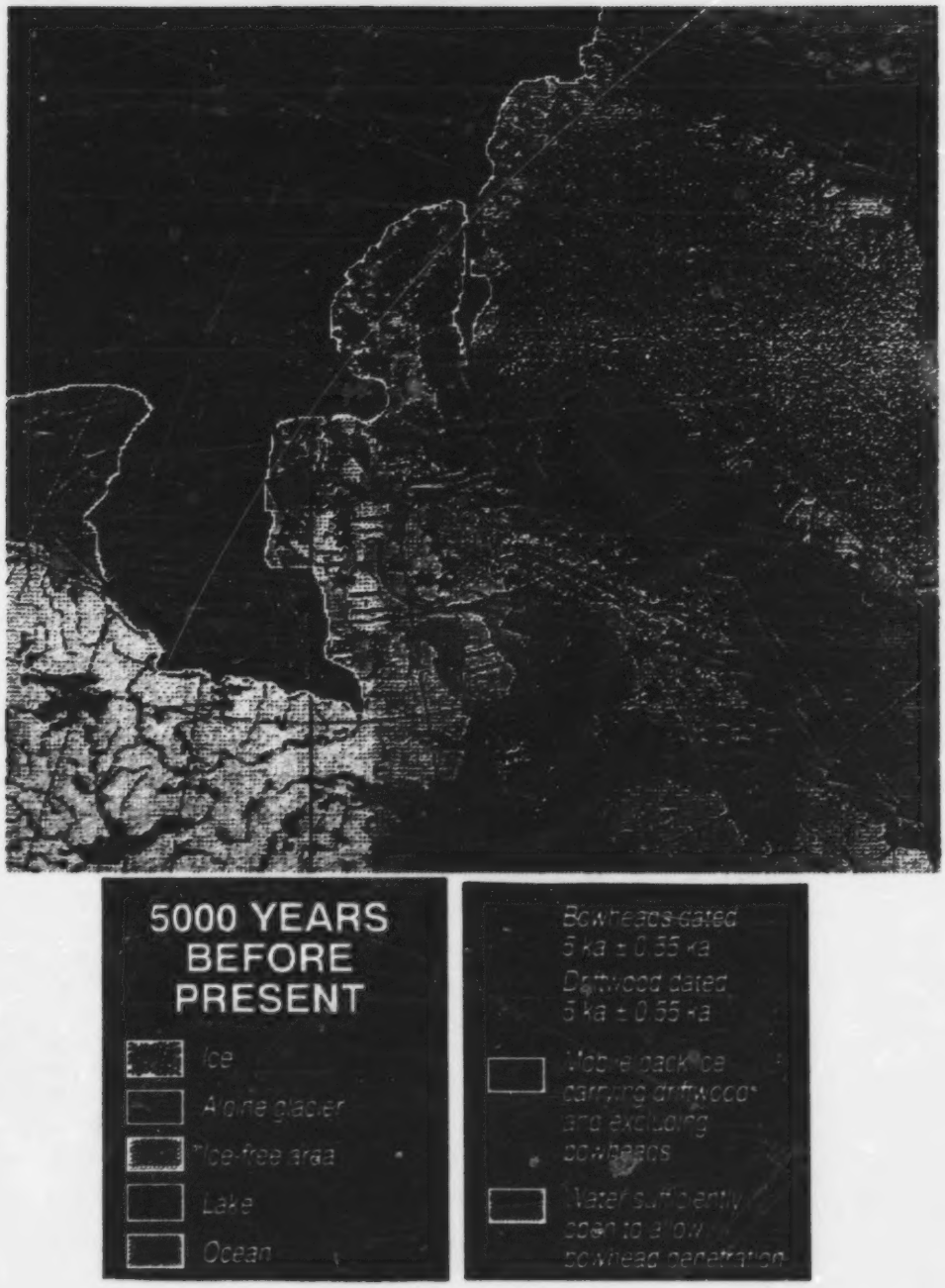


Figure 6. Paleo-sea ice distribution (Dyke and Morris, 1989).

Increased *in situ* melting of sea ice in the central Arctic channels would have diminished the re-exportation of the ice rafted wood. This situation is thought to be most akin to sea ice conditions likely to be found mid-way through the next century. This level of field detail is very difficult to obtain and currently, not particularly correlative with numerical climate models. Nevertheless, by analogy it is able to describe a scenario of future ice extent in the Canadian arctic archipelago during a climate warmer than at present.

Discussion

59. In summary, both numerical models and paleoclimatic work agree that sea ice extent and dynamics have not been static over time, nor are they likely to remain so with climatic amelioration over the next century. For the moment this does not give cause for concern. Nevertheless, there are significant geopolitical, and military operational/strategic issues that will need to be considered as a result.

60. From a geopolitical aspect, Canada will have to consider how it intends to deal with the issue of arctic sovereignty. For the present, many observers believe that whether the Northwest Passage is or is not an 'Internal Waterway' as claimed by Canada in 1973, is a moot point since it is not, by most standards, navigable. For most of the year, transit is blocked by ice in its widest part, Viscount Melville Sound, and it is necessary for vessels to retreat to passage through the Prince of Wales Strait between Banks and Victoria Islands, as happened with the voyages of the supertanker S.S. Manhattan in 1969 and the icebreaker U.S.S. Polar Sea in 1985. On both occasions there was considerable protest from the Canadian public. Notably, these events were about 15 years apart and this was the frequency of debate. With increased economic activity being brought about by an enhanced ice-free shipping season and freer access to natural resources, the level of debate (and DND's participation in it) will certainly increase.

61. The Manhattan voyage resulted in the enactment of The Canadian Arctic Waters Pollution Act in 1970. The legislation provided for the protection of ocean waters north of 60°N latitude for a distance of 160 km offshore (Fig.7).

Figure 7. Formal boundaries claimed by Canada in the Arctic, 1970-87 (Honderich, 1987).

Although at the time the Act was protested by the United States, it has been seen in Canada as good for the environment and to further establish our sovereignty over arctic internal waters. Obviously, any increase in shipping due to climatic amelioration will put added pressure on DND resources to aid in the protection of these waters.

62. The practical outcome of this is that one needs naval vessels capable of operating in ice-infested waters - something that Canada currently does not possess. At the present time, without heavy icebreaker support, which itself is limited, Canada's Navy is active only in two oceans. Even from a commercial viewpoint, only CANARCTIC's icebreaking freighter M.V. Arctic is capable of operating virtually year round in ice-covered waters. Consideration should be given to our naval operational future in the Arctic and our ability to design and build vessels tailored for that environment.

63. To better assess DND's future in arctic waters, further scientific research is needed on sea ice extent and dynamics, especially how it relates to global warming. There are also strategic aspects to the results of this research. For example, it is important to know how sound propagation will change in arctic water, how thermoclines will migrate, circulation patterns will be modified, and ice will ground (One of the predictions of a changing ice regime is that as ice cover lessens in the Arctic Basin, icebergs, ice floes and 'bergy bits' will become as much as three times more frequent along the east coast.). Aspects of these subjects are important for anti-submarine warfare and arctic acoustic surveillance.

PERMAFROST REGIONS

64. The permafrost zone of northern Canada (Figure 8) is one of the physical environments most susceptible to change from global warming. The effects of any change in the stability of ground temperatures would be profound, especially for organizations such as DND which possess considerable infrastructure such as runways, roads, fuel distribution networks and buildings in the region. Design and maintenance of these systems in a ground ice environment is a significant and costly operation for DND, even today.

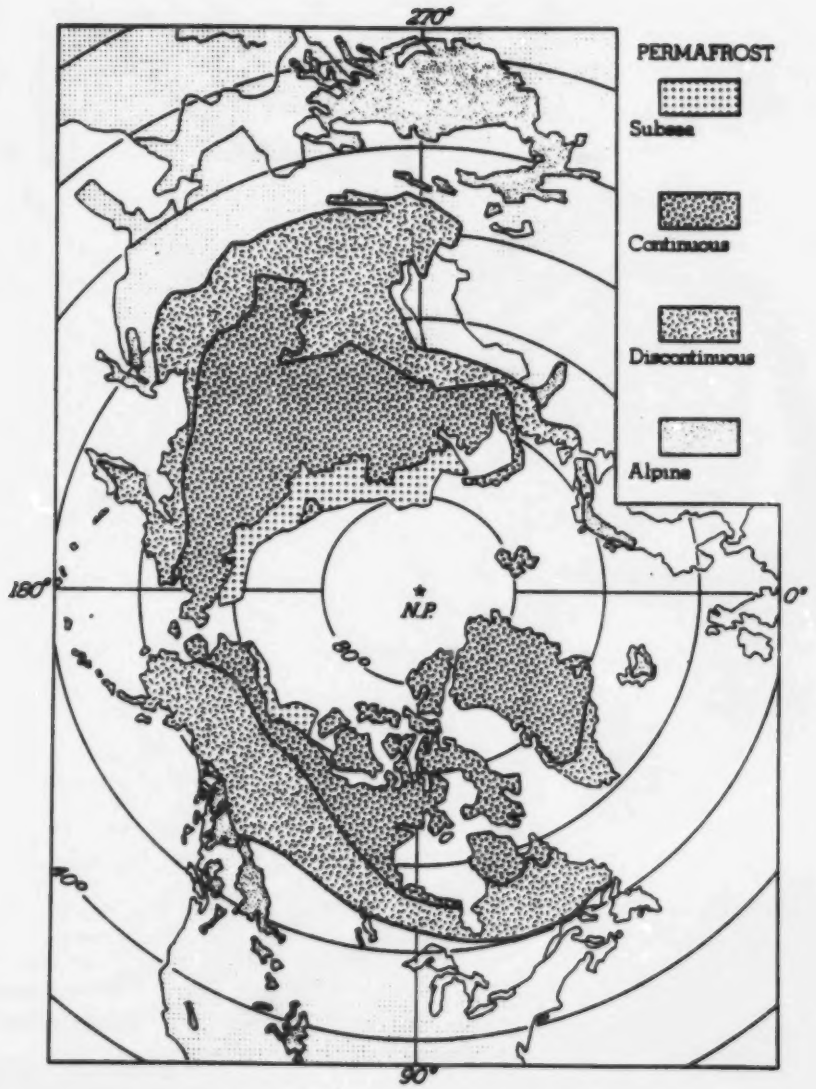


Figure 8. Existing permafrost distribution (Judge, personal communication).

Future climatic amelioration will probably exacerbate this situation.

65. Permafrost is defined as a thermal condition of the ground in which the temperature remains lower than 0° C for at least two consecutive years, regardless of other properties including moisture content and lithology (Washburn, 1973). The existence of permafrost depends on the heat balance at the earth's surface and the conduction of heat through the active layer or zone of annual thaw. Permafrost occurs in rock, soil, and dry or wet materials, where it may exist as pure ice, ice lenses or interstitial (pore) ice. It may also be dry where it exists in bedrock absent of moisture or ice due to mineral impurities, salinity, capillary pressure or lack of porosity. Most permafrost contains large amounts of moisture in the form of ground ice.

Distribution and Stability

66. Close to 24% of the earth's land surface is underlain by permafrost; it is particularly extensive in northern North America, Eurasia, Antarctica and Greenland. Permafrost extends over 40-50% of Canada's area, some 5 million km^2, and is a significant component of the arctic ecosystem. However, since the southern extent of permafrost is more sensitive to changes in climate, the existence of permafrost here will be of considerable importance in a scenario of climatic amelioration.

67. Permafrost distribution in Canada varies quantitatively from the continuous zone in the north to the southern discontinuous and sporadic zones (Fig. 9). It also occurs in shallow offshore environments that have previously been above sea level, such as the Beaufort Shelf. In the continuous zone, permafrost is assumed to occur within one metre of the surface to hundreds of metres in depth in a variety of terrain types, with the exception of deep lakes and river channels or newly deposited unconsolidated sediments. Depths of more than 1000 m have been noted by Judge (1973) in northern Canada. The development of permafrost to such thicknesses requires the persistence of suitable climate on a geological time scale, thus, to some extent, the depth of permafrost is dependent on its age. According to Sulman

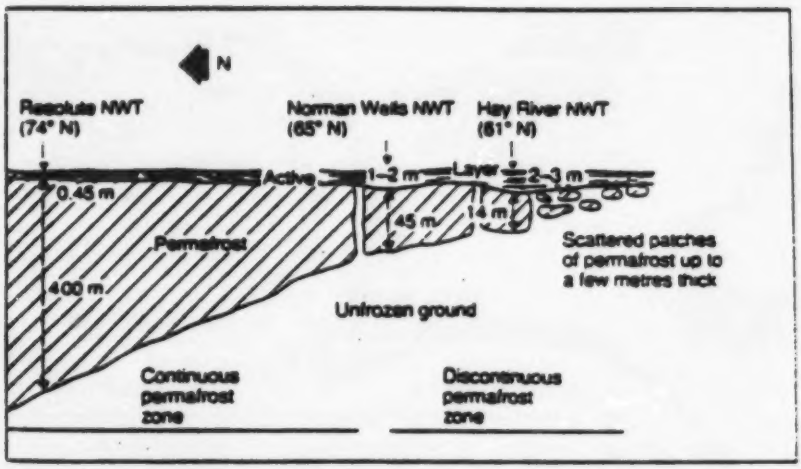


Figure 9. Vertical and north-south permafrost distribution (Williams, 1986).

(1982), thaw rarely exists between 0.5 and 700 m from the surface. Continuous permafrost gradually gives way to seasonally frozen discontinuous or 'warm' permafrost in combination with unfrozen material. In this zone, permafrost varies from widespread distribution interrupted by isolated taliks (thawed zones) to predominantly thawed zones at the southern fringe containing many sizes of erratic frozen islands and relic bodies insulated by surface cover. As discussed by Martinello (1988), distribution is controlled by microclimate and historical climatic factors. The sporadic zone is located south of the area of discontinuous permafrost. Within this area, it occurs in less than 30% of the terrain as ice lenses in localized patches of close to one metre in thickness, mainly under peat bogs. Judge (1972) indicates that sporadic permafrost is partly a function of variable surface conditions, and partly a disequilibrium response to increasing surface temperatures above 0° C.

68. Although permafrost is directly temperature dependent, its occurrence also depends on several local and other climatological factors. Some of the factors such as topography, altitude and latitude are relatively static in time, however, the majority are time dependent and closely interrelated. Whenever the average annual temperature is within a few degrees of 0° C, variations in surface conditions (vegetation, topography, hydrological conditions, solar exposure, and snow cover) determine where thermal conditions will be low enough to sustain permafrost. Even in very cold regions, however, there are still gaps in the permafrost, due primarily to the presence of water bodies which do not freeze to their bottom in winter. These non-homogeneous characteristics of permafrost with the scattered nature of direct observations, make precise mapping of permafrost and ground thermal conditions difficult. They also make it difficult to develop an accurate assessment for permafrost responses to global climate change.

The Effect of Climate Change on Permafrost

69. Since permafrost is a thermal condition, it is determined by climate and is potentially sensitive to climate change. Recent work by climate modellers, e.g. Smith (1986) and Wetherald and Manabe (1986), concluded that large areas of permafrost will disappear and the associated terrain will change as climate

ameliorates during the early part of the next century. Many thousands of square kilometres of permafrost, especially within the discontinuous zone, are within 1-2° C of the melting point and are particularly vulnerable to climatic warming. Temperature records from oil wells and bore holes in northern Canada, Alaska, Russia and Norway demonstrate that the upper layers of permafrost have increased in temperature over the past 50 -100 years (Lachenbruch et al., 1989; Balobaev, 1985; and Taylor, 1990). Warming in the North's mean annual surface temperature of up to 11° C in winter and 2° C in summer (8° C annual average) will initiate long-term changes in permafrost distribution. Active layer depth would rapidly increase and permafrost thickness would decrease as the depth to permafrost table lowered and the depth to base rose. Active layer thaw depth may be up to 50 cm more in winter-concentrated warming, as opposed to a distinct summer warming (Smith et al., 1983a). Eventually, permafrost would degrade, most visibly commencing in the marginal areas where mean annual ground temperature is close to the freezing point (Smith, 1986). Yellowknife and Inuvik Forward Operating Location (FOL) sites, for example, could be susceptible to degradation of runways, roads and building foundations.

70. Permafrost in the western Arctic, particularly the Mackenzie Valley development corridor, is relatively warm and exists in poorly consolidated material high in ice content. As a result, the active layer has reduced bearing strength and weaker bonding . It is subject to high subsidence, thaw, ground settlement and thaw consolidation (Smith et al., 1983b). In these areas, permafrost recession might be in the order of 1-4 m over the next 25 years (Smith et al., 1983a).

71. There is no consensus on the changes likely to occur within the continuous permafrost zone due to climate change. However, major differences are not expected, except for localized disappearances due to microclimate (Goodwin et al., 1984) and some warming of the profile. Of more immediate importance would be the various rapid onset effects in areas of thaw-sensitive permafrost. Global warming of 2.8-5.2° C in the mean annual air temperature as predicted by general circulation models (Environment Canada, 1990; Tucker,

1989), could cause the upper layers of permafrost (0-5 m) to change temperature and to thaw relatively quickly- on the order of decades (Street and Melnikov, 1990).

72. Rapid topographic changes would be associated with the onset of ground ice melting in the ice-rich contact zone at the top of permafrost (Smith, 1986). The frozen ground surface currently provides thermal stability over permafrost. As it degrades and loses strength, thermokarst, drainage disruption and slope instability will ensue. The geomorphology in areas of marginal permafrost would be most affected by climatic warming. Mass downslope movements including slope failure , mass wasting, slumping, solifluction and mudflows will be common as depth of thaw increases. Surface processes and phenomena such as the formation of patterned ground, ice wedge and frost cracking, frost heave and soil creep will probably increase in the initial stages of climate warming. Also, beaded streams may become more prevalent, particularly within the discontinuous permafrost zone (Judge, 1972).

73. Temperature change is not the only process likely to affect permafrost with ameliorating climate. Summer and winter precipitation may increase significantly. As discussed under "Meteorology", increased rainfall in a given area would tend to enhance evaporation rates and cloud cover which would in turn reduce insolation and ground surface temperatures, thus resulting in a negative feedback to a rise in mean annual surface temperature. Although not discussed above, the melting of permafrost would also result in the release of methane and, to a lesser extent, CO_2 from previously frozen biological material and from gas hydrates. The extent to which these feedback loops will enhance the greenhouse effect is uncertain, but it could be as much as 1° C from methane alone by the middle of the next century (Street and Melnikov, 1990).

74. Fluctuations in the extent, thickness and temperature of permafrost have occurred before in response to climate change. For the present, the expected warming of arctic temperatures has not been visibly established on the

landscape. Lachenbrunch et al. (1982) have calculated that the global climatic warming of the last 100 years has been insufficient to reduce permafrost thickness by more than 80 cm. The active layer in the sensitive western Arctic probably deepened by no more than 10-20 cm during the same time period. In addition, relict islands of permafrost that remain south of the present boundary suggest that it extended over a much broader area until widespread climatic warming occurred (Goodwin et al., 1984). The thermal history of the western Arctic (ie. the Holocene warm period about 10 ka BP) and the associated landscapes as reconstructed by proxy data suggests that similar active layer changes, ice wedge truncation, and permafrost degradation can be expected with future warming trends.

Discussion

75. The consequences of global climate warming to continued permafrost stability are profound. In general, the effects of the projected warming during the next several decades would deepen the active layer and initiate a northward retreat of permafrost. It is expected that a 2° C global warming would shift the southern boundary of the climatic zone currently associated with permafrost north and northeast by at least 500-700 km. The southern extent of permafrost will lag behind this, moving only some 25-50 km in the next 40-50 years. The depth of the active layer is expected to increase by one metre during the same time frame (Street and Melnikov, 1990).

76. From DND's point-of-view, these events will have a significant operational impact. In practical terms, increased terrain instability would lead to major concerns for the integrity and stability of roads, airfields, dams, reservoirs, and other engineered foundations located within affected areas. Deepening of the active layer would subject building and bridge foundations to continuing deformations as a result of thaw settlement. Decreases in the amount of ground ice present would lead to decreases in the mechanical strength of the associated soil as well as increases in permeability, both of which will have significant consequences for engineering of facilities and overland mobility.

77. It is possible given the current state of knowledge and design constraints to predict areas that will be particularly susceptible to permafrost degradation. Seto (1986) has carried out this exercise with several climatic models, an example of which is shown in Figure 10. Most of the FOL airstrips are located within this zone, though it must be noted that the affected areas are highly dependent on which climate model is chosen as a reference. A recent study by Judge and Tucker (1990) has mapped sub-surface conditions at FOL sites in Inuvik and Rankin Inlet with ground penetrating radar. Zones of massive ground ice were detected below the proposed extensions. The authors concluded that in areas slated for construction or modification of drainage patterns, the identification of sub-surface permafrost features ahead of events can play an important part in the planning process to avoid future problems. As a note, current engineering at the Rankin Inlet FOL expansion is allowing for some degree of future climate change (Béland, DCEDE, personal communication).

78. There are several approaches to designing structures located within permafrost (Street and Melnickov, 1990). Possibilities may be to: a) disregard the thermal regime of underlying permafrost and apply conventional techniques of construction from temperate regions; b) thaw permafrost prior to construction; c) allow for thawing during construction, and; d) maintain permafrost in a frozen state. Of these options, a) is a very risky procedure, b) is very expensive and not widely used, and c) is only of benefit for short-term construction or where materials are thaw-stable. Option d) is currently in wide use throughout the North. Raised utilidors in Inuvik, and insulated runways at Rankin Inlet are examples of such a design philosophy.

79. Another permafrost stability issue that DND may need to analyze is that of overland summer mobility. Although we assume that given our current level of activity there is no mobility problem (since most of transport is by air) this situation may not remain so in the future. In addition, since the

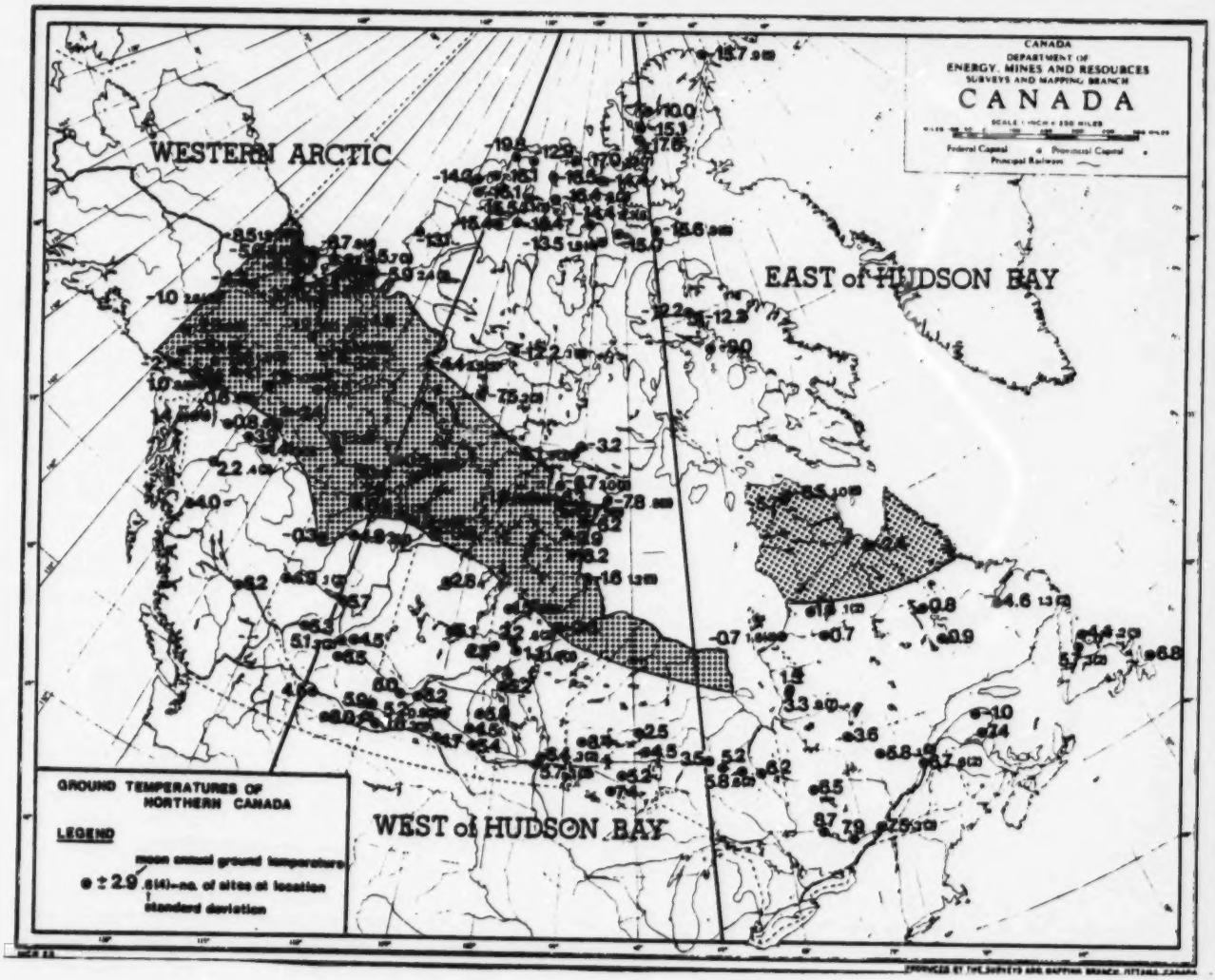


Figure 10. Permafrost areas susceptible to degradation (Seto, 1986).

existing road network will be especially vulnerable to thaw, perhaps catastrophically, the design parameters of low ground pressure / high mobility vehicles for the CF might profitably be given renewed consideration. Further pro-active research may also be needed on the question of permafrost stability as it pertains to our existing infrastructure. If decisions are made to carry out such projects, they could be done through the Defence Research Establishments in conjunction with groups like the National Research Council and Nodwell and General Motors Canada, all of whom are involved in mobility or cold weather research.

80. The policy aspects of DND operations in the North are very much related to permafrost degradation. It may also be that the non-military level of activity in the North will increase in the future as climate becomes more amenable. New possibilities for economic activity will open up and settlements will be created where they are not currently viable. As occurs with most expansion into new territory, an enhanced DND presence in parallel with this growth would most likely occur. Despite climatic warming, doing business there will become more, not less, expensive. Street and Melnikov (1990) cite examples of remedial work to an Alaska runway costing $6-8 million, repairs to a 100 m long thaw settlement problem on the Dempster Highway requiring $100,000 in engineering studies and $150,000 in repair work. How much DND is prepared to pay for new facilities and for remedial measures on existing infrastructure will require considerable thought.

TREE LINE AND ECOZONES

81. Along with permafrost boundaries, early change in response to climate warming also includes high latitude tree line and tundra boundaries. As a topic unto itself, the actual movement of the tree line and ecozones in any given direction is not of fundamental importance to the Department, however, from a general socioeconomic perspective, and therefore indirectly to DND, the issue is important and worthy of discussion in this paper. Also, according to Fyfe (1985), the sensitivity and relative non-complexity of the northern biological system enable it to reflect fundamental trends in the rate of

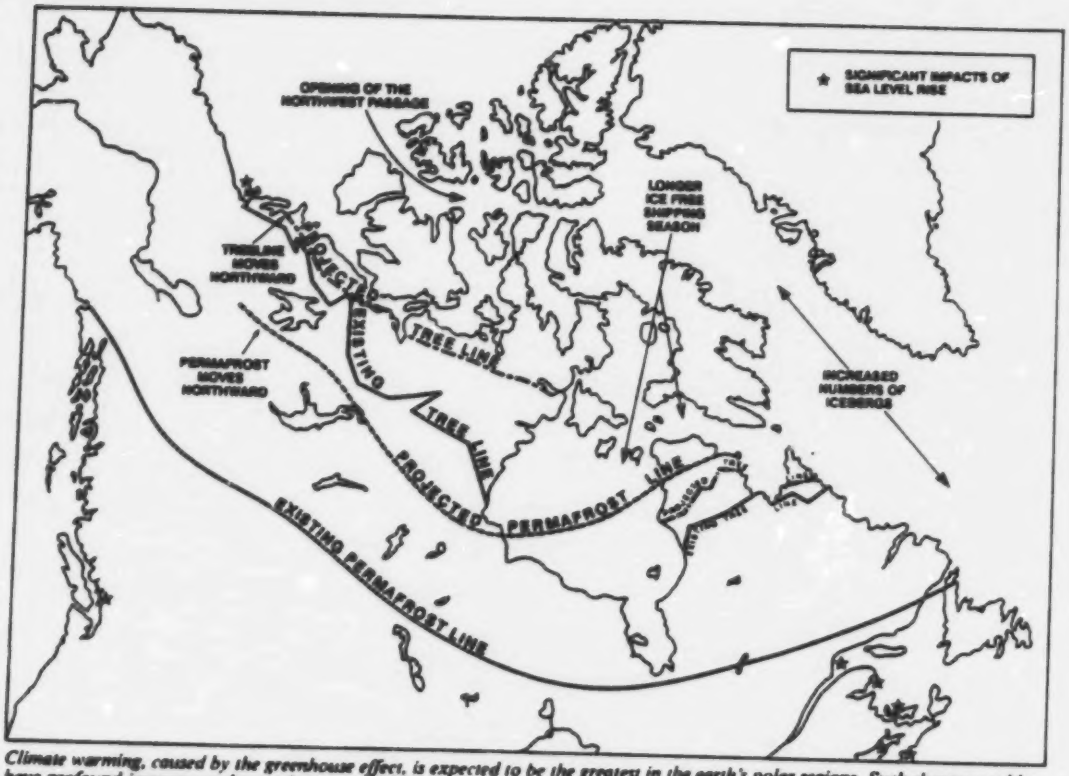
global climatic change. Hence, the tree line will act as a long-term indicator of climatic and ecological change.

82. The tree line is expected to migrate northward 280 km beyond the current location as productivity, regeneration success, biomass, and decomposition increase. Coincident permafrost degradation will enhance some of these processes and inhibit others through its influence on the soil thermal and moisture regimes and through thermokarst. The northward migration of the tree line will affect soil development. Models of CO_2-induced tree line dynamics are limited, and instrumented and observational evidence of change is highly variable. Ground temperatures provide a more accurate reflection of changes in the geothermal regime affecting growing conditions.

Tree Line Dynamics

83. The Canadian tree line is a phyto- or bio-geographic boundary that delimits a major discontinuity in vegetation, soil, topography, physiology, wildlife, and climate. At some locations the position of the tree line on a map has been extrapolated because of lack of data, but general confusion regarding its location arises from the incompatibilities and variations in criteria used to describe it. On a map of air photos, the tree line is a visible line winding unevenly from the Mackenzie Delta to the northeast tip of Manitoba at Hudson Bay (Fig. 11). On the east side of Hudson Bay, it runs northeast from Lac Guillame Delisle to Ungava Bay.

84. For the purpose of this study, it is convenient to define the tree line as a reflection of an unstable climatic boundary. Most commonly, the tree line is regarded as the boundary coincident with the 10° C daily mean July air temperature isotherm (the warmest summer month). The forest-tundra ecotone separates the boreal forest from the tundra and includes the various forms of the tree line. The 'tree line' may be used interchangeably with the term 'forest-tundra' since as a biogeographical boundary the tree line is not a sharp line of forest discontinuity, but a transitional zone between forest and tundra over a 20 to 550 km distance (Brysen et al., 1964).



Climate warming, caused by the greenhouse effect, is expected to be the greatest in the earth's polar regions. Such change would have profound impacts on the northern way of life.

Figure 11. The tree line in Canada (Atmospheric Environment Service, 1989).

85. Though the extent of the tree line is mainly controlled by temperature, the intensity, frequency and degree of dominance of summer Arctic air masses also influences the northern distribution of forest. Edlund (1986) describes these air mass patterns:

> In general, the northern limit of boreal forest occurs where cold, dry arctic air masses exist at least 50% of the year. The predominance of arctic air masses increases with latitude. The northward penetration of trees is limited by the summer mean position of the Arctic Front from July through October (Edlund, 1986; Bryson et al., 1964; and Barry, 1967). The tree line is considered as the climatic boundary between northern Arctic air and southern Pacific or continental pressure cells. In effect, the cold Arctic Ocean depresses summer temperatures north of the tree line. Northwest of the continental interior, the positions of the Arctic Front and the tree line are restricted by the anchoring effect of the Northern Cordillera on upper atmospheric westerly waves (Nichols, 1976).

Northern Vegetation in the Postglacial Climatic Optimum

86. Present day plant communities do not always reflect their maximum range extension since the last glaciation. During the Hypsithermal (postglacial climatic optimum), boreal forest and plant assemblages similar to those of the present forest-tundra ecosystem extended far beyond their current positions, especially in the far northwestern mainland of Canada (Ritchie, 1984). This is thought to have been in response to a mean summer temperature at least 2° C warmer than today. Impact predictions of climate change on the tree line require an understanding of the dependence of natural ecosystems on current climatic conditions (Edlund, 1986). Because this knowledge is limited, the location of the modern tree line can justifiably be compared to that of the Hypsithermal. As with the previous discussion of sea ice, this analogue is useful in predicting the effects of a 2-5° C summer warming on the tree line.

87. The vegetation response to the Holocene warming trend was not uniformly timed across the continent. The boreal forest reached its maximum extent in northwestern mainland Canada, where it stretched to the Beaufort Sea coast, around 9.0 to 8.0 ka BP (Ritchie, 1984). In Keewatin the maximum extent of boreal forest was reached around 6.0 ka BP (Nichols, 1974). In Ungava, the

maximum extent of boreal forest was around 5.0 ka BP (Short and Nichols, 1977; Payatte and Gagnon, 1985). In some places, the boreal forest extended roughly 250 km north of the modern forest limit (Bryson et al., 1965).

88. Beginning approximately 8.0 ka to 6.0 ka BP in the western Arctic mainland (Ritchie, 1984) a regional climatic cooling brought about the southward retreat of the boreal forest margin. The forest-tundra ecotone and forest limit has remained roughly in the same position since about 4.5 ka BP. In central Keewatin, forest retreat occurred at around 4.0 ka BP, and in Ungava, around 3.0 ka BP (Nichols, 1974, 1975; Short and Nichols, 1977; Short, 1978).

89. In the High Arctic, the climatic optimum occurred around 4.0 ka to 3.3 ka BP. This is generally detected by the increase in peat development. There is evidence to suggest that modern High Arctic plant assemblages extended into areas that currently do not harbour them. For example, fragments of birch have been found in organics dated ca. 8.0 ka BP in west-central Ellesmere Island (Hodgson, 1985), a Low Arctic species that does not grow in the region today. Blake (1974) also found a flora from Holocene peat on Bathurst Island which was more diverse than the present one.

Impacts of Climatic Change on Arctic Vegetation

90. Impact predictions of climatic change on arctic vegetation are constrained by the limits of climate models and the known links between vegetation and climate (Edlund, 1986). Nevertheless, the current predictions are that a twofold increase in CO_2 would lead to an annual temperature increase that would have an impact on the distribution and vigour of vegetation at higher latitudes. How soon these changes would be detected, and what would be the resultant vegetative patterns, are not clear. According to Edlund, the lag time required for a detectable range extension could be in the order of several hundreds to several thousands of years.

91. As with forecasts of sea ice extent, the Holocene climatic optimum may serve as a good modern analogue for predicting the effects of a 2-3° C warming

of summer temperatures. A reduction of summer temperature gradients and a displacement of mean July isotherms northward are likely. However, an increase would be maintained in the gradients around the major water bodies, because these would still cool the air that passes over them. Warmer summer temperatures and lengthened growing seasons would allow some plants to re-extend their ranges northward. Scrub and dwarf shrub tundra and sedge meadows would probably become richer and extend further north, probably into the Arctic Islands. The 10° C mean July isotherm would extend well into the southern Arctic Islands, resulting in a climate that would support spruce and tall deciduous shrub growth on Banks, Victoria, and Baffin islands, as well as parts of the northern mainland. Probably, spruce would be unable to reach these islands, particularly in the time frame of a few centuries. Instead, there might be an enhancement of both the density and height of low shrubs, similar to that found around Tukoyaktuk today, and the development of tall willow thickets along deep water courses and lake shores (Edlund, 1986).

92. If climate warming is accompanied by an increase of available moisture during summer, then there would be an expansion of wetland communities in lowlands, and an increased accumulation of peat, especially in the boreal forest zone, forest tundra ecotone and the scrub tundra zone. Further, if the warming trend extended into the highest latitudes, the area of minimal vegetation would eventually be reduced, possibly to a narrow strip along the northern coast of the Queen Elizabeth Islands. The warm belt of the northeastern Queen Elizabeth Islands would also show enhanced vegetation growth, but probably not an invasion of southerly species, because of its geographic isolation.

93. Edlund (1986) proposes a second option which is that plant communities with no modern analogues might develop in the Arctic. A contrasting scenario for the impact of climatic warming in the world (Emanuel et al., 1985) predicts an extension of drier communities into high latitudes; that the Arctic Islands would be covered with desert communities with pockets of desert bush. The boreal forest would be drastically reduced to a small part of northern Ungava and southern Baffin Island. Steppe vegetation would cover

most of the northern mainland of Canada west of Hudson Bay and temperate forest would occur on the east side of James Bay.

94. This drastic switch to true desert communities is not likely since this scenario assumes no increase in available moisture, thus linking modern precipitation levels with higher summer temperatures. In addition, the model does not account for unmeasured moisture available from the melting of ice in the soil, and does not consider that an increase in temperature would likely result in a greater proportion of the Arctic Ocean becoming ice-free in summer. This would increase cloud cover, fog and precipitation in regions near open water. Edlund notes that the reliability of these two scenarios cannot be meaningfully tested. They simply point out the necessity of incorporating information about vegetation, surficial material, vegetation and moisture preferences, and the relationship between modern climate and vegetation into future models.

The Ecosystems of Canada in 2050

95. To expand on Edlund's analysis of future tree lines, Rizzo (1990), describes ecosystems of Canada in the year 2050. His scenario shows a very different Canada (Fig. 12). It is no longer characterized by broad, homogeneous, east-west bands as at present. A complex mosaic of ecosystems, some new, others modified in location and in extent, reflect the response of ecosystems to warmer climate. This scenario, however, does not directly consider other ecological factors such as soils and water. Thus, areas classified as temperate may be dissimilar to present temperate ecosystems. In time, soils will adjust, reflecting the changes in the climate, a new water balance will develop and a new equilibrium will be established. The changes in the extent of the ecoclimatic provinces are summarized in Table 1.

96. As noted in the table, the colder ecoclimatic provinces will cover less area than at present. Generally, the ecoclimatic provinces will shift northward and grow larger. The Subarctic virtually disappears. This results in a Boreal-Arctic interface, something that Canada does not have now. The Subarctic province is smaller than at present and extends into areas now

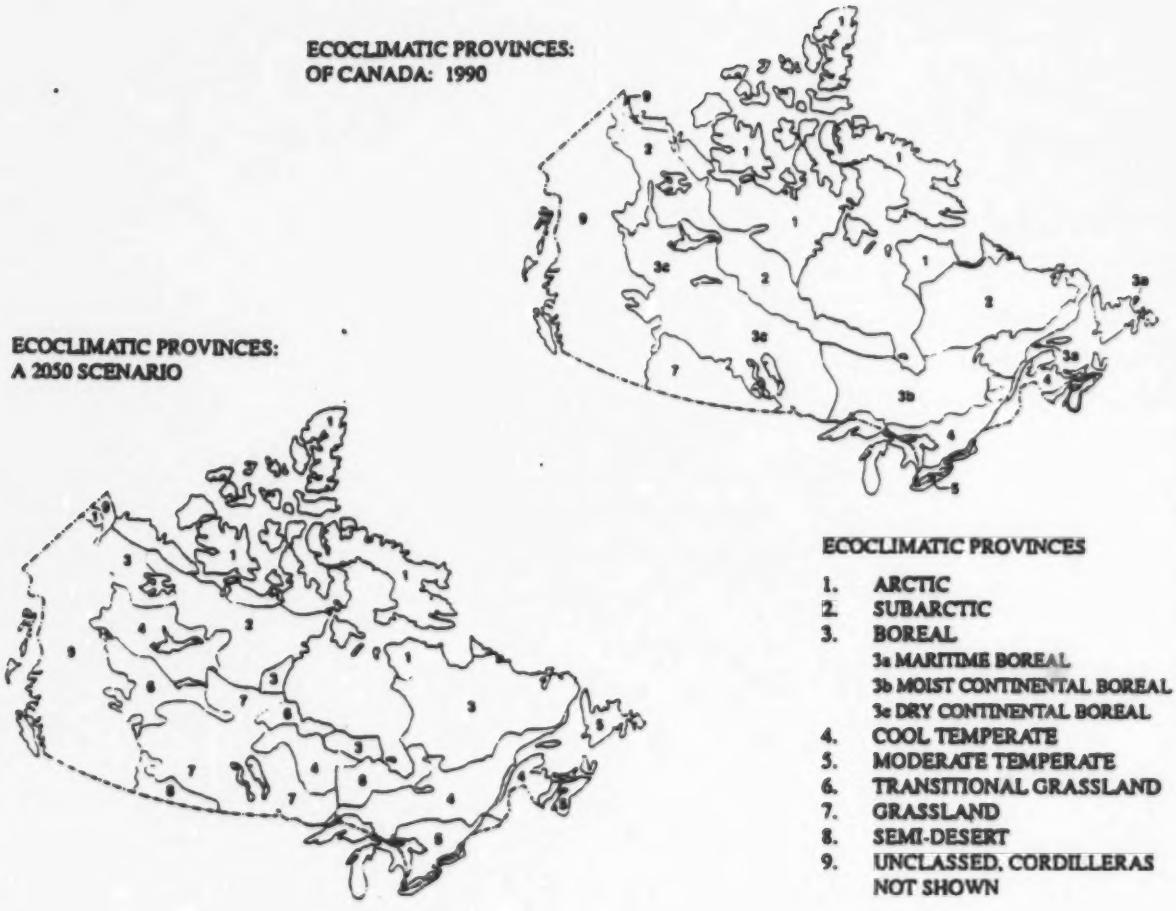


Figure 12. Current and future ecoclimatic provinces (Rizzo, 1990).

TABLE 1. ECOCLIMATIC PROVINCES OF CANADA

Ecoclimatic Province	Area of Canada (%)		
	Current	Future	Change
Arctic	26	20	-6
Subarctic	20	8	-12
Boreal	29	15	-14
Cool Temperate	4	15	+11
Moderate Temperate	<1	5	+5
Grassland	5	12	+7
Transitional Grassland	0	8	+8
Semi-Desert	0	2	+2

characterized as Arctic. The Arctic provinces are limited to a small band on the northern coast of Canada and the Arctic Islands.

97. The pervading influence of climate change on ecosystems can be illustrated by some of the implications to forestry. There could be a dramatic change in forest distribution. Tree lines could migrate northward and species adapted to the changed climate will replace our current forests. However, in some areas of suitable climate, such as the Canadian Shield region west of Hudson Bay, other factors such as soils may not be suitable to support forests.

Discussion

98. The practical aspects of northern shifting tree lines and ecosystems only concern DND in so far as they relate to the economic activities of Canadians in the North. As Canadians find more reasons to populate the North, DND will be expected to participate in the overall activities of the territory. From the above information it is concluded that migration of tree lines and ecozones will happen with less rapidity than will the disintegration of permafrost, for example.

99. Nevertheless, there are aspects of northern migration of the tree line that will directly effect DND. The most important of these is the increased risk of forest fires. Future climate warming will result in far more dead and diseased trees ready to fuel fires. Forestry officials state that this is one of the most significant aspects of northern climate migration (Hall, personal communication).

100. As the summer of 1990 in arctic Canada has shown, forest fires in northern regions, where communications and infrastructure are poor, habitually evolve into situations that are profound disasters partly because of our inability to deal with them. DND has as one of its mandates aid to civil authorities, and as the organization with one of the largest groups of personnel in the North, it is and will continue to be incumbent on the CF to aid in such activities as fire-fighting and other environmental disasters. As

the risk of severe fire increases over the coming decades, DND policy and logistics may require modification to accommodate the new situation.

SUMMARY AND CONCLUSIONS

101. That the process of global climate change will affect arctic Canada is virtually indisputable. The timing and degree are less sure. Current best estimates by the international scientific community is that global mean temperature is projected to increase at a rate of 0.3° C per decade during the next century. Increases may be greater over land surfaces than over the oceans and will be far greater in northern latitudes in winter. Uncertainties in the projections with regards to timing, magnitude and regional patterns of climate change can be attributed to the limited resolution and refinement of existing general circulation models. Paleoclimatic research can only offer analogous situations for comparative purposes and is not really helpful with timing and extent.

102. Despite the existing uncertainties, the level of knowledge is such that it can be stated that the predicted rise in temperature and changes in precipitation and weather circulation patterns will have significant impacts on the operations and policy of DND in four obvious environmentally sensitive areas, i.e. meteorological conditions, sea ice extent and dynamics, permafrost stability and tree line / ecosystem migration. It is concluded that:

A. Arctic meteorological conditions are from certain aspects likely to deteriorate in the next century. Although temperatures are predicted to rise as much as 8° C, this will lead to more open water and, therefore, longer and more frequent periods of fog. Increased open water will also lead to greater amounts of clear air turbulence and higher sea states. DND will need to be able to better predict long range weather conditions and movement of pack ice; in essence there will be a need for an expanded military meteorological presence in the Arctic.

B. Sea ice extent will be significantly less than exists today. Because of this, navigation through the Northwest Passage will become routine and economic activity will increase. It is also possible that climatic amelioration will result in increased challenges to our claims of sovereignty over arctic internal waters. From an operational standpoint, DND will have to give more thought to our ability to navigate through ice-infested waters. Such a capability is non-existent today. This will require more research to be carried out on, among other topics, ice-sensing technologies and marine vessel engineering.

C. Permafrost stability in Northern Canada is most likely to decrease during the next century. This will have profound effects on DND infrastructure such as runways, buildings, fuel storage installations, roads and communications facilities. The costs incurred to keep soil frozen or otherwise adapt infrastructure will be considerable. Operations that involve overland mobility will also be affected. DND may profitably join other agencies in cooperative research on the likelihood of site-specific permafrost such as at the FOL sites or CFS Alert. At the same time, mobility of tracked and wheeled vehicles should be more thoroughly investigated.

D. The tree line is expected to migrate northward by at least 280 km beyond the current location as productivity, regeneration success, biomass and decomposition increase. Generally, the ecoclimatic provinces will shift northward and grow larger. It is concluded that migration of tree lines and ecozones will happen with less rapidity than will the disintegration of permafrost, for example. Forestry officials state that one of the most significant aspects of northern climate migration is the increased risk of forest fires. DND has as one of its mandates aid to civil authorities, and as the organization with one of the largest groups of personnel in the North, it will be incumbent on the CF

to aid in such activities as fire-fighting. As the risk of severe fire increases over the coming decades, DND policy and logistics may require modification to accommodate the new situation.

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GLOSSARY

ACTIVE LAYER
: The top layer of ground above the permafrost table that thaws each summer and refreezes each fall, and varies in temperature and thickness both temporally and spatially.

ADIABATIC
: The relationship of pressure and volume when a gas or other fluid is compressed or expanded without either giving out or receiving heat.

ADVECTION
: The horizontal movement of a mass of air that causes changes in temperature or in other physical properties of the air. Advection fogs are especially common at sea where warm moist air is transported over cold ocean currents of high latitudes.

ALBEDO
: The percentage of the incoming radiation that is reflected by natural surface by a natural surface such as the ground, ice, snow or water.

ASPECT
: Appearance, composition, or inferred environmental implications of a particular assemblage.

BAROCLINITY
: The state of stratification in a fluid in which surfaces of constant pressure (isobaric) intersect surfaces of constant density (isoteric).

CLIMATE MODEL
: The behaviour of the components of the earth's climate system is determined on a physical basis from the fundamental laws of nature, and expressed mathematically to best simulate in a physically consistent manner the present climate and how that climate would change in response to some external forcing mechanism.

CONTINUOUS PERMAFROST
: Permafrost occurring everywhere beneath the exposed land surface throughout a geographical regional zone with the exception of newly deposited unconsolidated sediments, where the climate has just begun to impose its influence on the ground thermal regime. From the southern to the northern limits, thicknesses range from between 100 m to 1 km, active layer depths from 30 cm to 1 m, and temperature at depth of zero annual amplitude from -5 to -20^{0} C.

CONVECTION
A process of mass movement of portions of any fluid medium (liquid or gas) due to differences in density, generally brought about by heating.

CUMULUS CLOUD
Compact heaped-up cloud masses with flat bases and rounded tops.

DISCONTINUOUS PERMAFROST
Permafrost occurring in some areas beneath the ground throughout a geographical zone where other areas are free of permafrost, where the active layer does not always extend to the permafrost table and unfrozen layers may occur between frozen ones. Thicknesses range from 10 cm at the southern limit to 100 m where the zone grades into continuous permafrost, and the depth of zero annual amplitude lies between 0 and -5° C in the same direction.

ECOSYSTEM
Interrelationships between all living organisms and their biotic and abiotic environment.

ECOTONE
A transition zone between two adjacent ecological communities usually exhibiting competition between organisms between organisms common to both.

FOREST-TUNDRA ECOTONE
Biotic transition belt between the limit of dense, continuous boreal forest and the treeless tundra, including the tree line. It forms a distinct ecosystem extending in a circumpolar range 2.5 to 3×10^6 km^2 between the polar limit of tree growth and the economical forest line.

GEOTHERMAL GRADIENT
Rate of temperature rise with depth below the ground surface.

GREENHOUSE EFFECT
The thermal result of the fact that comparatively short wave length solar radiation penetrates the atmosphere rather freely, only to be largely absorbed near and at the earth's surface, whereas the long wave length terrestrial radiation passes upward with great difficulty.

GYRE
A circular or spiral motion or form, especially as it refers to an ocean current.

HYPSITHERMAL
Postglacial warm period extending from about 7000 to 600 B.C. responsible for the last 2 m eustatic rise of sea level. The climatic optimum.

HOLOCENE
The postglacial Recent Period, that is the last 10,000 years.

INVERSION
A reversal of the normal atmospheric temperature gradient.

KA B.P.
Thousand years before present where 'before present' is 1953 by convention.

LEAD
A channel of water, especially through a field of ice.

MELTWATER
Water resulting from the melting of snow or glacier ice.

MICROCLIMATE
The detailed climate of a very small area, e.g., a single forest, over which small variations exist from place to place , differing from the general climate of the surrounding region

OCCLUSION
The front formed by a cold front overtaking a warm front and lifting the warm air above the earth's surface.

OCEAN MIXED LAYER
Uppermost ocean layer in a coupled climate model wherein temperature is relatively uniform with depth (generally to 70 cm).

PALEOCLIMATE
The climate of the world through the geologic ages. Its data are the distribution of glacier deposits, nature of plant and animal fossils, topography and geography of former periods, and character of sedimentary rocks.

PERMAFROST
The thermal condition in soil or rock where temperatures below freezing persist over at least two consecutive winters and through the intervening summer. Perennially frozen ground is a thermal state of earth materials regardless of water or ice content.

POLYNA
A semipermanent area of open water in sea ice.

SIGNAL-TO-NOISE RATIO
The ratio of the signal (difference between experiment and control situation) to noise, the greater the size of which determines the distinctness of the experiment from the control situation. To increase the ratio, noise can be reduced by averaging over longer time periods, extending the length of the simulation or the magnitude of the signal can be increased.

SOLIFLUCTION
The movement over the permafrost table of a thin detached veneer of vegetation and mineral soil as the active layer thaws.

STRATOCUMULUS CLOUD
Soft, low, grey layer cloud, often with a lumpy appearance.

TALIK
A layer of unfrozen ground between the seasonal frozen ground (active layer) and the permafrost. An unfrozen layer within the permafrost.

THAW SETTLEMENT
The generally differential downward movement of the ground surface resulting from the escape of water upon the melting of excess ice in the soil, and the thaw consolidation of the soil mass.

THERMAL CONDUCTIVITY
The ability of a material to conduct heat in a steady state, varying within a particular material with density and water and ice content.

THERMOCLINE
A stratum in which the temperature declines at least 1° C with each metre increase in depth.

THERMOKARST
The process of differential thaw settlement or caving and subsidence of the ground because of melting of ground ice, loss of volume, and thermal erosion.

TROPOPAUSE
The upper limit of the troposphere - in the middle latitudes, generally 10-12 km above the earth's surface.

TUNDRA
A vast treeless windswept rocky generally level to undulating region of lichens, mosses, sedges, grasses, and some low shrubs including dwarf willows and birches, characteristic of the Arctic and higher alpine regions.

UTILIDOR
A heated overland network of large diameter pipes designed to provide municipal services (sewer, water, etc.) in areas of severe northern climate. One of the most intricate is located in Inuvik, NWT.

WISCONSINAN
The fourth, and most recent, of the Pleistocene glaciations.

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Meteorology
Sea Ice
Paleoclimate
Permafrost
Tree Line
Vegetation
Arctic
Mobility
Tundra
Climate
Sovereignty
Policy